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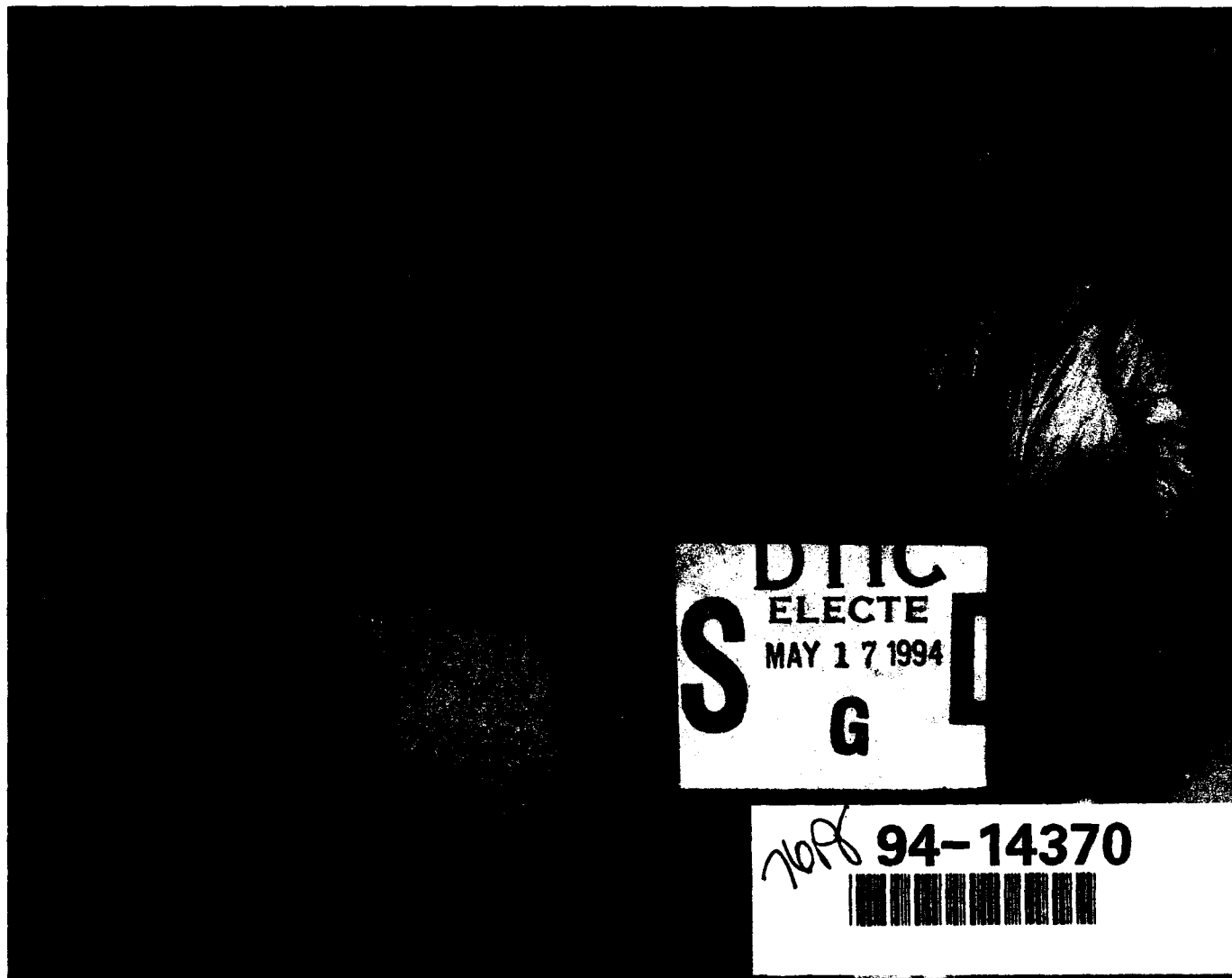
Department of Energy/Office of Nonproliferation and National Security

DOE/AN/ACNT-94A



# Arms Control and Nonproliferation Technologies

First Quarter 1994

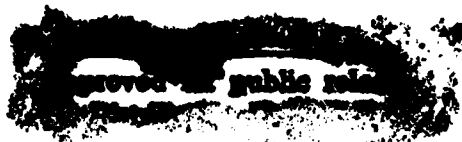


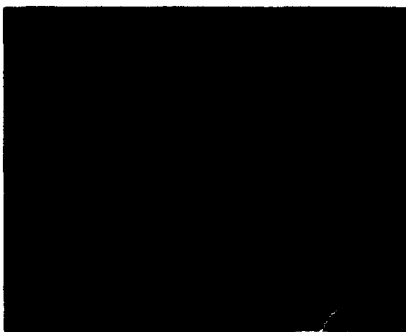
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## The Non-Proliferation Experiment





### **The cover**

A cement plant or a large bakery? No, it's the ANFO/emulsion explosive mix being unloaded from an agitator car and then flowing through auger tubes to the explosion chamber of the DOE's Non-Proliferation Experiment. To find out more about the process of setting up the experiment, see photos beginning on page 10.

The purpose of *Arms Control and Nonproliferation Technologies* is to enhance communication between the technologists



who develop means to verify compliance with agreements and the policy makers who negotiate agreements.

## **The DOE Non-Proliferation Experiment**

In this issue of *Arms Control and Nonproliferation Technologies* we present the initial findings of the recent Non-Proliferation Experiment (NPE), conducted by the Department of Energy at the Nevada Test Site. Through an introduction and pictorial walk-through, Marv Denny and Jay Zucca of Lawrence Livermore National Laboratory describe the overall experiment. This is followed by scientific and technical abstracts of the complex suite of experiments and analyses, which were presented at the Symposium on Non-Proliferation Experiment Results and Implications for Test Ban Treaties, April 19-21, 1994.

Questions regarding the ongoing analysis and conclusions from the NPE should be directed to Leslie Casey in the Office of Research and Development within the Office of Nonproliferation and National Security of DOE. Her phone number is 202-586-2151.



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## Introduction: DOE Non-Proliferation Experiment

*Marvin D. Denny and John J. Zucca  
Lawrence Livermore National  
Laboratory*

Every year tremendous amounts of chemical explosives are used world-wide in mining, quarrying, and civil engineering projects. In the United States alone, for example, industrial explosions of 50 tons or more number in the thousands.<sup>1</sup> Such industrial projects create a challenge for policy makers molding a test ban, since they could provide the necessary cover for clandestine nuclear tests.

To address this critical verification issue for the current Non-Proliferation Treaty (NPT) and for a possible future Comprehensive Test Ban Treaty (CTBT), the Department of Energy sought to measure certain differences between underground nuclear tests and chemical tests in the same geology, so that other explosions could be identified. This was done in a field experiment code-named the Non-Proliferation Experiment (NPE).

The U.S. Department of Energy detonated approximately 1.29 million kg of a commercial blasting agent at the Nevada Test

Site on September 22, 1993, at 00:00:01.080 AM Pacific Daylight Time. The blasting agent, based on ammonium nitrate and fuel oil (ANFO), was emplaced in a cylindrical chamber, approximately 15.2 m in diameter by 5.5 m high, located at 37.20193° N and 116.20986° E in a Rainier Mesa tunnel, 390 m underground. The explosion had an energy release of approximately 1 kt (1 kiloton =  $4.186 \times 10^{12}$  joules).

This comprehensive experiment was designed to determine the signatures of chemical explosions for a broad range of phenomena and compare the signatures with those of previous nuclear tests. If significant differences can be measured, then these measures can be used to discriminate between the two types of explosions. In addition, when these differences are understood, large chemical explosions can be used to seismically calibrate regions to discriminate earthquakes from explosions. Toward this end, on-site and off-site measurements of transient phenomena were made, and on-site measurements of residual effects are in progress.

Although seismic data have been collected on both chemical and nuclear explosions over the

last several years, the differences between the two sources have been difficult to assess due to path differences, variations in the geologic emplacement conditions, and the amount of energy released. These difficulties were minimized in the NPE because it was detonated in the same geology and within 500 m of several prior nuclear explosions of comparable energy. Thus, regional seismic signals between the NPE and nearby nuclear explosions can be compared directly.

### Types of data gathered

A successful experiment yields many types of data. The NPE was extensively instrumented at ranges starting within the blasting agent itself and extending to regional (less than 2000 km) and teleseismic (greater than 2000 km) distances. Within the blasting agent, several time-of-arrival cables and two particle-velocity gages were emplaced to determine the actual energy release. Approximately 50 accelerometers and stress gages were deployed underground to track the shock wave's evolution to an elastic wave. On the mesa's surface, more than 60 stations recorded the seismic wave to determine the extent of spall and to locate aftershocks. The permanent networks within and around the Nevada Test Site and approximately 400 portable stations in the western U.S. tracked the regional seismic wave evolution. Other phenomena recorded were the electromagnetic pulse, hydroacoustic signals, electrical resistivity on the mesa above the

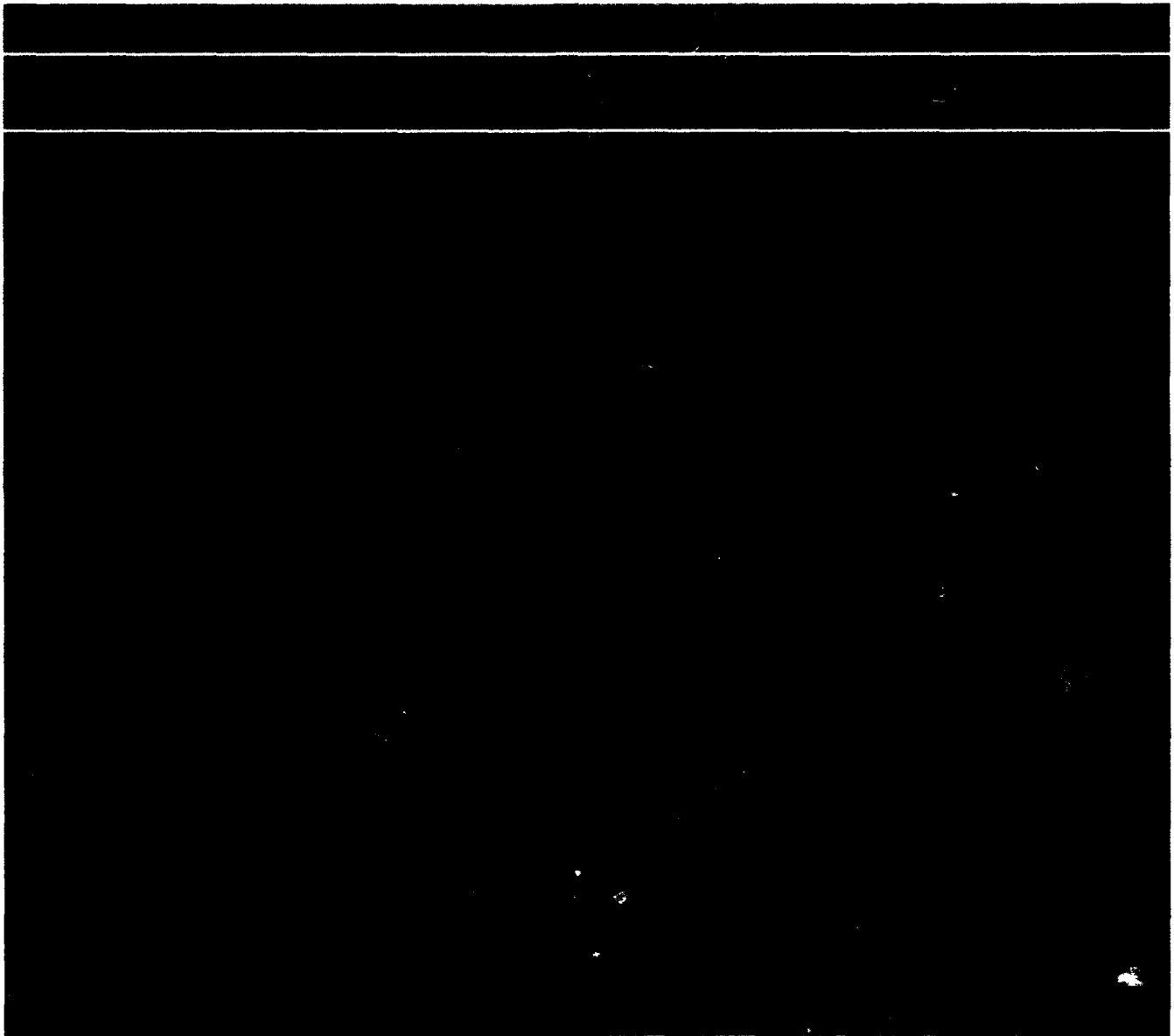


cavity, thermal emissivity, and other surface changes (the last two were inferred from multispectral imagery acquired by flyovers before and after the explosion).

### **Experimentalists sharing data**

The experimental measurements were carried out by many U.S. government agencies and

laboratories, universities, private companies, and foreign participants. The initial indications are that all the experimentalists enjoyed a very high success rate. Over 90% of the systems



deployed produced useful data. All parties who collected data have agreed to exchange raw data, which is now available through the courtesy of the Incorporated Research Institutions for Seismology (IRIS) to interested researchers.

Following the pictorial overview that begins on this page, we present abstracts from the Symposium on the Non-Proliferation Experiment Results and Implications for Test Ban Treaties. The overall purpose of

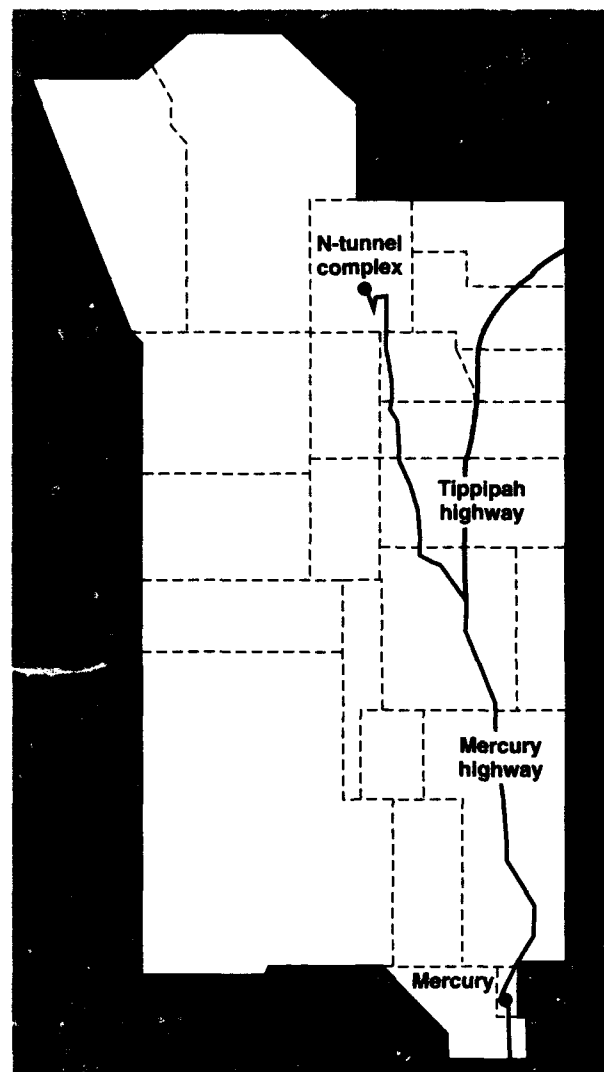
the symposium is to share the NPE results and examine the implications for test ban treaties. Later this year a proceedings will be published with the full technical papers and results of the NPE.

### Reference

1. P. G. Richards, D.A. Anderson, and D.W. Simpson, "A Survey of Blasting Activity in the United States," *Bull. Seis. Soc. Amer.*, **82**, 1416 (1992).

*The photos and drawings following give an overall picture of the step-by-step process to set up the Non-Proliferation Experiment (NPE). The individual experiments are described within the abstracts of the conference, which follow this section. The NPE would not have been possible without the infrastructure of the Nevada Test Site and its workers. Photos in this section were taken by the photography staff at the Test Site. Drawings are adapted from ones by Paul Thompson, LLNL/NTS.*

■ Figure 1. A map of the Nevada Test Site, showing the route to and location of the N-Tunnel complex, where the Non-Proliferation Experiment took place.



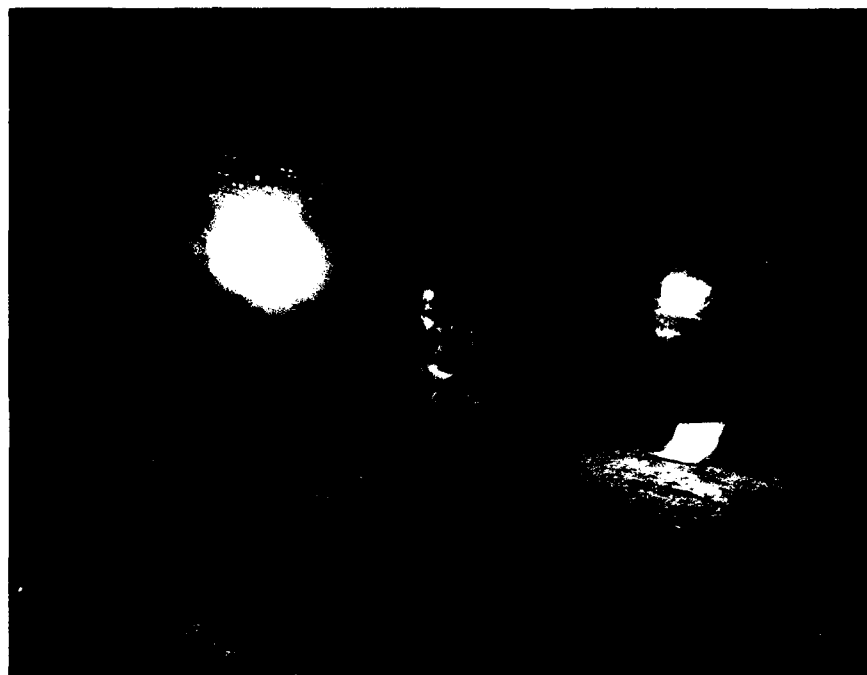


■ *Figure 2. Aerial view of the N-Tunnel entrance and associated staging area.*



■ *Figure 3. The Alpine miner apparatus that drills the original shafts into the bedrock of the tunnel.*

■ **Figure 4.** A view from the back wall of the chamber looking toward the access drift. Mining of the chamber is nearing completion in this photo. The overhead pipe is for ventilation.



■ **Figure 5.** Chamber mining is complete. Auger pipes in the notch in the ceiling await the ANFO/emulsion mix. CORRTX time-of-arrival cables crisscross the room at three levels. The points at which they cross approximately define the axis of the cylindrical chamber. The scaffolding in the center of the room is for the installation of the detonator charges along the axis and was removed prior to installation of the ANFO/emulsion mixture.





■ *Figure 6. Scientists from Los Alamos prepare particle-velocity gages for installation in the rock near the chamber wall.*

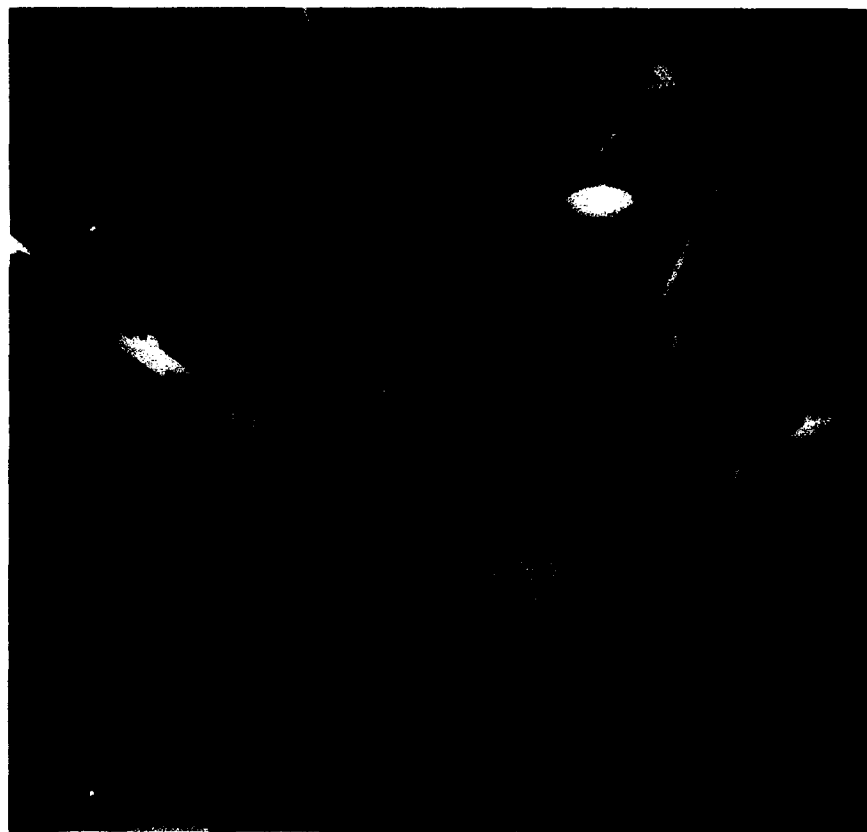


■ *Figure 7. Tom McKown (second from left) leads a team of scientists from Los Alamos installing close-in instrumentation that will be used to measure time of arrival and ground motion associated with the planned explosion.*

■ *Figure 8. Looking toward the portal of N-Tunnel in an alcove near the explosion chamber. Two LANL particle-velocity gage installations are visible on the right wall. On the ceiling and upper walls are the cables that led to the recording equipment in another alcove.*

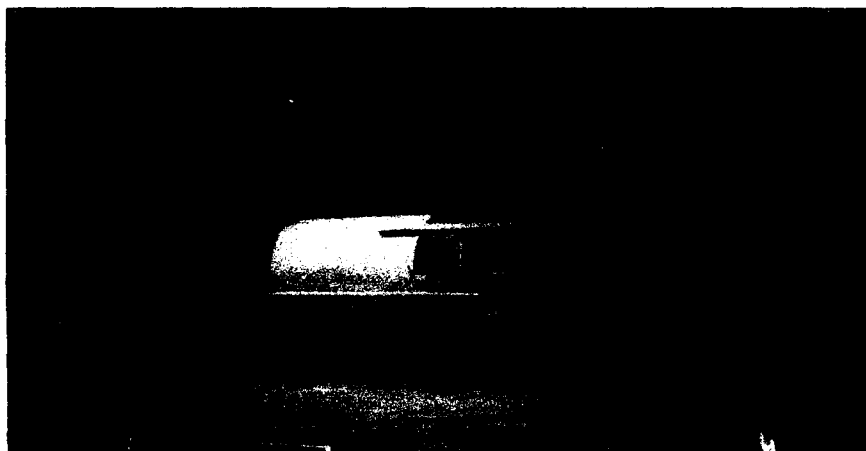


■ *Figure 9. The instrumentation alcove where all of the LANL and Sandia subsurface ground motion data were recorded.*





■ *Figure 10. Five equally spaced, high-energy booster charges, emplaced along the axis of the chamber, were used to detonate the blasting agent.*



■ *Figure 11. One of the explosive storage tanks for the ANFO/emulsion mix arriving at the N-Tunnel processing area.*

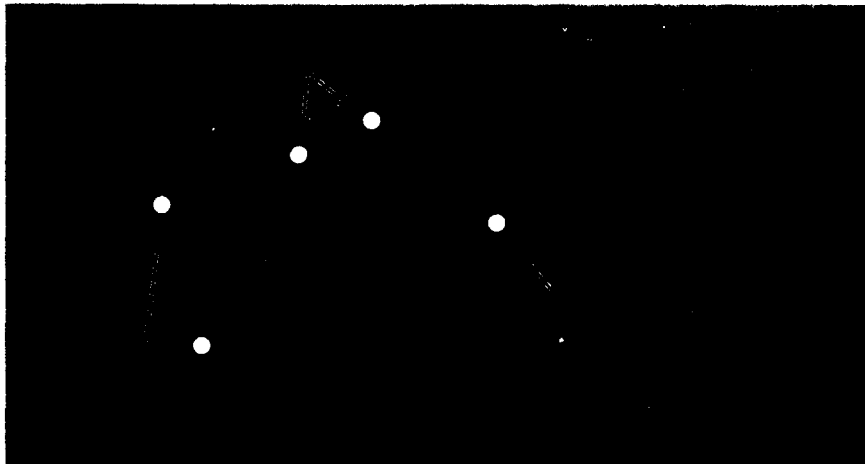
■ *Figure 12. The explosive blending area with its various tanks and trailers used for storage and mixing the 50/50 blend of ANFO and emulsion.*



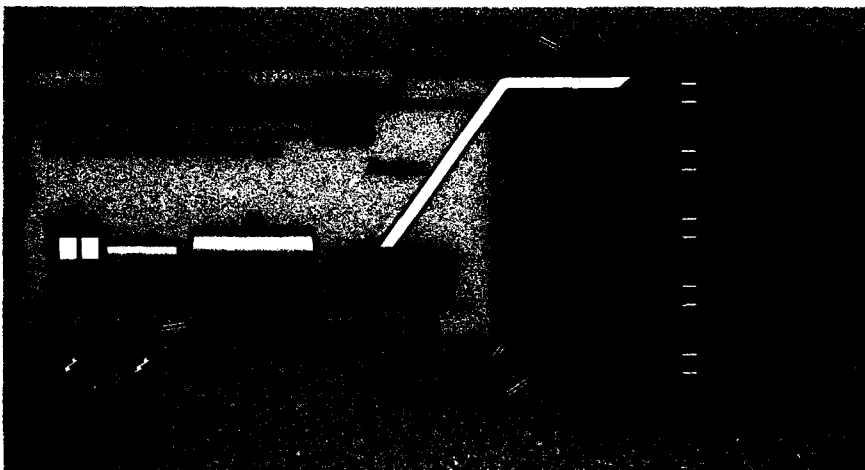
■ *Figure 13. The outdoor blending area in Area 12 N-Tunnel. An agitator car is being loaded with the explosive blend for transport underground to the explosion chamber.*







■ *Figure 14. N-Tunnel complex including the north extension drift, .23 access drift, .25 access drift, and the explosion chamber.*



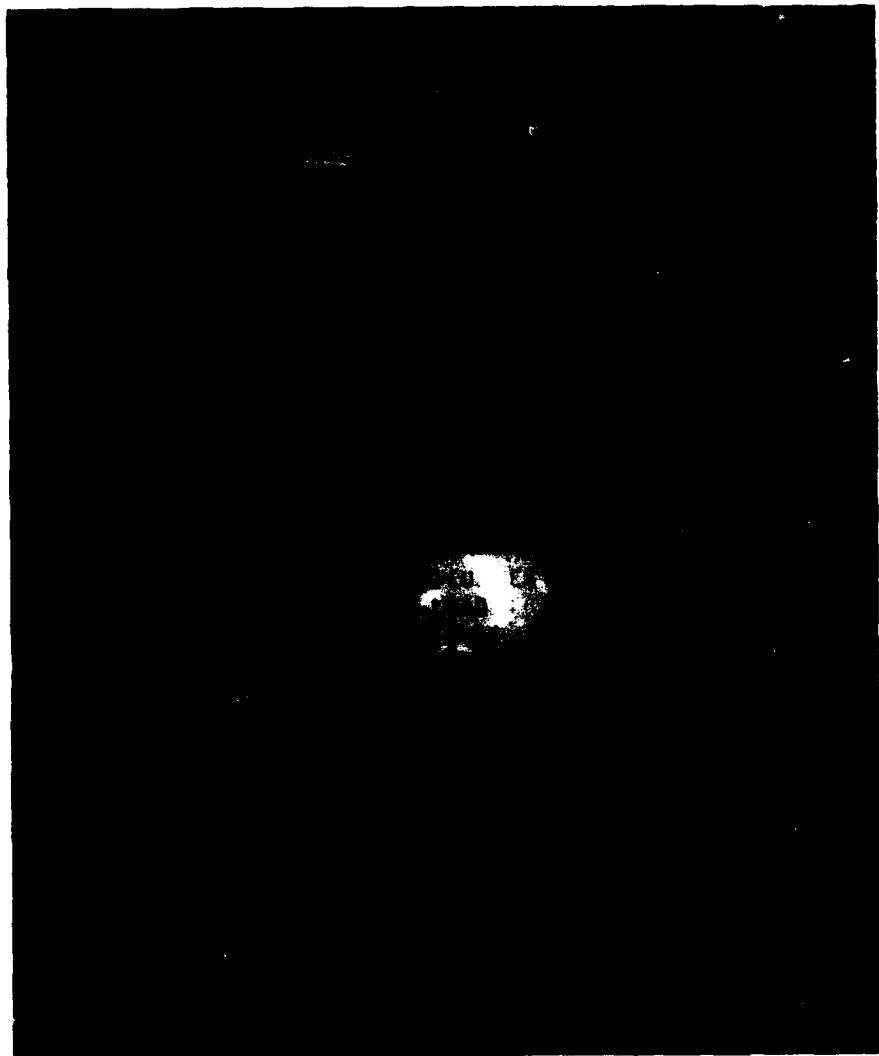
■ *Figure 15. Schematic of the ANFO/emulsion blend chamber and placement area.*

■ *Figure 16. The agitator car unloading the explosive blend. The two auger tubes transported the blend into the chamber.*



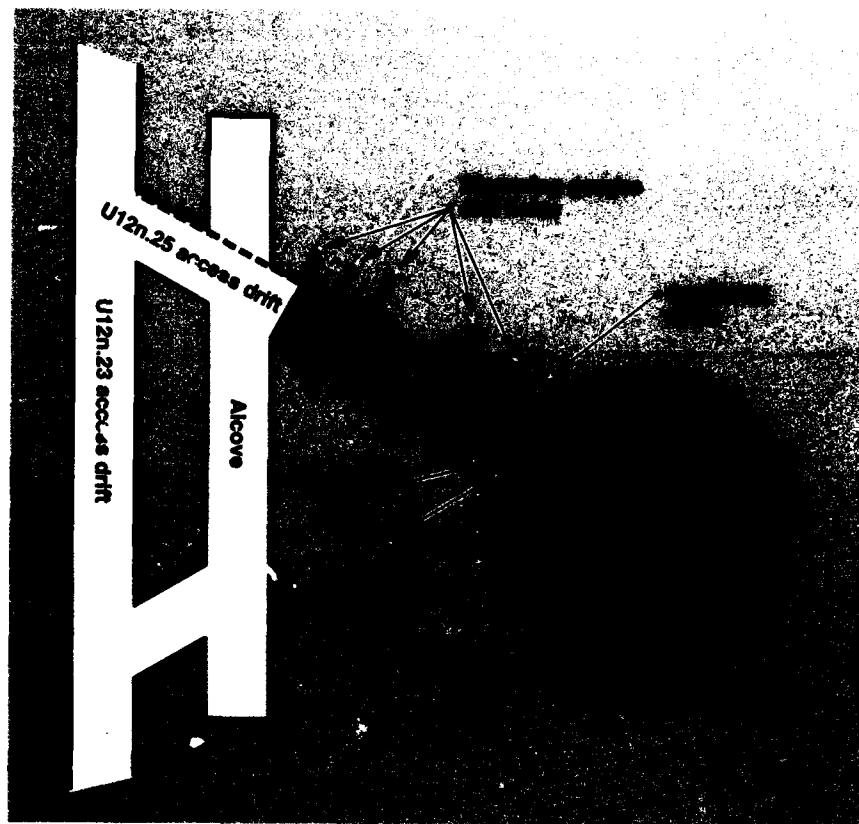
■ *Figure 17. A view through the top of the bulkhead into the filled chamber. The two large tubes at the top of the photo held the augers that filled the chamber with explosive blend. Notches in the ceiling held the tubes so the explosive could truly fill up the chamber.*



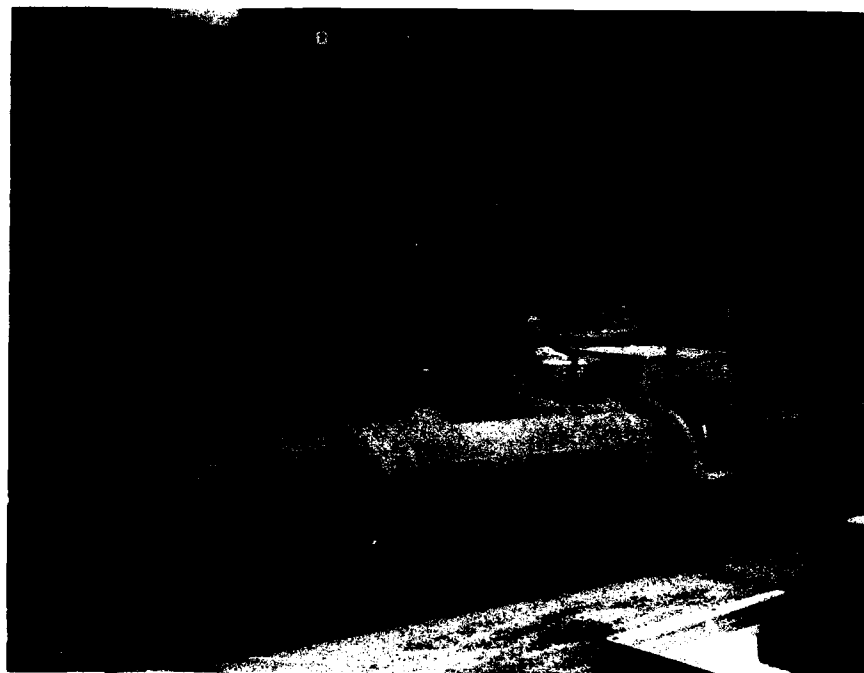


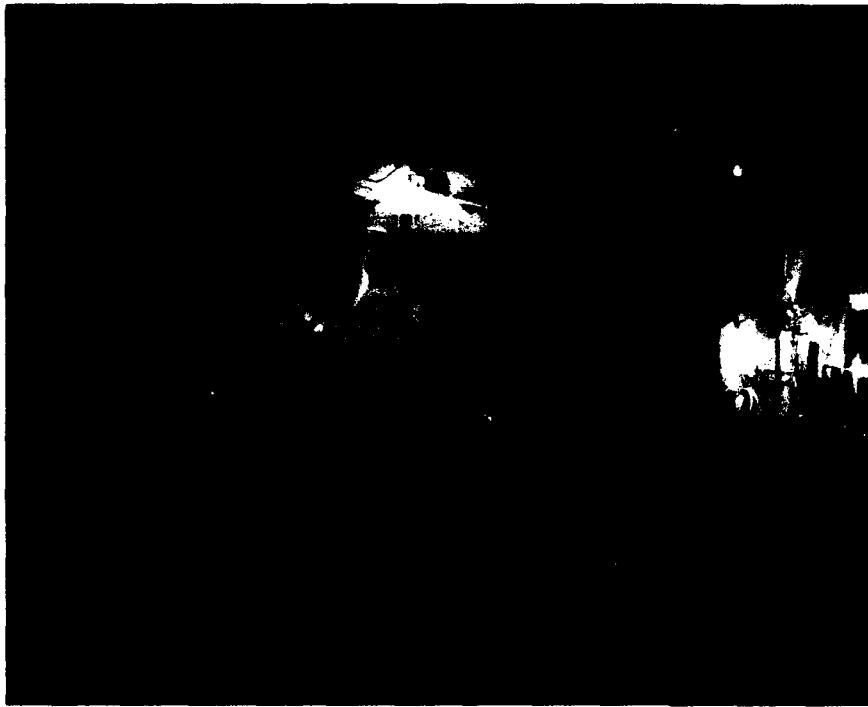
■ *Figure 18. The bulkhead from inside the access drift. The cylinder on the floor contains a tracer gas (sulfur hexafluoride), which will be used in conjunction with a barometric pumping experiment to measure migration of gas through the overburden rock to the earth surface.*

■ Figure 19. Schematic of the .25 drift stemming lifts, the bulkhead, and sandbags when the experiment components were in place.



■ Figure 20. An agitator car is loaded with grout for stemming the access drift to the chamber.





■ *Figure 21. The access drift after the grouting was completed. The alcove at the right had experiments emplaced along its near wall.*

## Overviews

### Experimental Objectives of the NPE

Robert G. Geil

*Lawrence Livermore National Laboratory, Livermore, CA*

The Non-Proliferation Experiment (NPE) involved many different organizations in an extensive experimental program to study problems in verification of a Comprehensive Test Ban Treaty. Participating organizations included the DOE National Laboratories, several universities, and foreign governments. The purpose of this paper will be to describe the experimental measurement program, which included extensive pre-shot, shot-time, and post-shot measurements to compare the information from the NPE with other smaller, conventional explosions and previous nuclear explosions.

Extensive measurements were made of the shock wave from the NPE, starting with close-in measurements in the ANFO/emulsion mixture itself, through its progression into an elastic seismic wave recorded at local and regional distances from the explosion. A small, 300-pound calibration explosion was

conducted in the middle of the chamber and later excavated for the NPE, so the experimenters could study scaling phenomena between conventional explosions that were 4 orders of magnitude different in size. Other experiments directed toward the problem of detecting and locating clandestine nuclear explosions included infrasound, ionosonde, and hydroacoustic measurements.

Experiments supporting on-site inspection technologies were conducted to explore either discrimination techniques to distinguish between conventional and nuclear explosions or techniques to locate and identify a clandestine nuclear explosion. The discrimination experiments included electromagnetic phenomena, local seismic stations, and visual observations. The suspect-site inspection experiments included gas sampling, aftershock, overhead imagery, and geophysical exploration techniques.

# The NPE and Comprehensive Test Ban Monitoring

W. J. Hannon

*Lawrence Livermore National Laboratory, Livermore, CA*

The Department of Energy, in cooperation with the Defense Nuclear Agency, conducted a 1-kiloton conventional explosion, the Non-Proliferation Experiment (NPE) at the Nevada Test Site, to gather experimental information in a major problem area for stability and verification of a Comprehensive Test Ban Treaty. The purpose of this paper is to set the stage for the NPE Symposium, including the threat to stability that comes from the potential for large conventional explosions such as the NPE to either be used to mask a clandestine nuclear test or be mis-identified as a nuclear test.

The experiment was conducted on September 22, 1993, in N-Tunnel in Rainier Mesa. The explosive consisted of 1.29 million kg of an ammonium-nitrate-fuel-oil (ANFO) and emulsion mixture that was emplaced in a 900-m<sup>3</sup> excavated chamber. N-Tunnel was chosen as the location for the cylindrical chamber because of its availability and the large number of previous nuclear explosions in the same immediate area. Extensive pre-shot, shot-time, and post-shot measurements were made to compare the results from the NPE with other smaller, conventional explosions and previous nuclear explosions.

Many different organizations participated in the experimental measurement program in areas involving close-in shock wave phenomena, seismology, infrasound, electromagnetic phenomena, and techniques for on-site inspections. Observers were invited from other U.S. Government organizations, from the U.S. public, and from foreign governments in order to achieve the maximum possible dissemination of information about the NPE.

The data collected during the experiment indicate that instantaneously detonated, spatially compact chemical explosions have regional seismic signals that are larger than, but otherwise similar to, the signals from nuclear explosions with similar yields buried at the same depth. These similarities suggest that conventional explosions detonated under these conditions could be used as surrogates for nuclear explosions in order to calibrate discriminants in specific regions. The results also underscore the fact that the effectiveness of current methods used to identify conventional mining and quarrying explosions do not depend upon the intrinsic properties of the interaction of the explosive with the immediately surrounding rock. Instead, they depend upon operational practices such as the temporal duration and spatial extent of the conventional explosion and its separation distance from a free surface.

The close-in electromagnetic measurements made on the NPE and on nuclear explosions indicate that the signals from the two types of explosions differ in their onset times and rise times. These differences may form the basis for useful confidence building measures that could be instituted if close-in monitoring is permitted on large, announced chemical explosions. Such confidence building measures would be particularly appropriate for those explosions whose yields and/or detonation conditions are such that regional seismic monitoring would be unable to determine whether a nuclear explosion had been detonated in place of or had been masked by the announced chemical explosion.

## **U.S. Comprehensive Test Ban Monitoring Goals**

*Lawrence Turnbull*  
*State Department*

The U.S. monitoring objective under a Comprehensive Test Ban Treaty is to determine the occurrence of a nuclear explosion of any yield conducted in any environment. This goal, though, is not practically achievable using the technical sensors that are available today or will be available in the near future. Therefore, balancing technical feasibility and cost, the U.S. technical monitoring goal is to detect, locate, identify, and attribute with high confidence evasively conducted nuclear explosions of a few kilotons' yield in geographical areas and environments of high interest.

Achieving this monitoring goal for the underground environment will be challenging, considering that the identification of nuclear explosions will take place within a "noise background" of a very large number of earthquakes and manmade non-nuclear explosions

that regularly occur at seismic magnitudes equivalent to a few kilotons evasively conducted—about a seismic body-wave magnitude range of 2.5 to 3.0. The requirement that this goal be met with high confidence means that the number of incorrectly identified events, or "false alarms," are reduced to a minimum. The technical community will need to develop robust seismic discriminates that provide statistical estimates of an event being an explosion or an earthquake. If, in this process, an event is judged to be an explosion, we will need to statistically estimate whether it is a single explosion or a series of explosions, the latter indicating that it could have likely had a chemical source. This information will then be used to examine other sensor data and to possibly initiate on-site verification measures.



# **Large Chemical Explosions in the Former Soviet Union and Blasting Estimates for Countries of Nuclear Proliferation Concern**

*William Leith*

*U.S. Geological Survey, Reston, VA 22092*

Monitoring a comprehensive nuclear test ban by seismic means will require identification of seismic sources at lower magnitudes, where industrial explosions (primarily mining blasts) may compose a significant fraction of the total number of events recorded and may, for some countries, dominate the seismicity. Thus, data on blasting practice have both political significance for the negotiation of treaties involving seismic monitoring of nuclear tests, which may require notifications for large chemical blasts, and operational applications for monitoring, both for estimating the number of seismic events to be monitored at various magnitude levels and for identifying effective blast discrimination techniques. While it is often asserted that mining explosions contribute significantly to seismicity at lower seismic magnitudes, the

rate of mining seismicity is unknown for most countries outside the U.S. Our reviews of geologic factors affecting seismic monitoring in 10 countries of nuclear proliferation concern suggest that blasting varies greatly from country to country.

The U.S. Geological Survey has recently obtained data on blasting activities in the former Soviet Union (FSU), one of the few countries whose use of explosive exceeds that of the U.S. A review of the Soviet data suggests that there are both similarities and differences in blasting practices between the U.S. and the FSU. These data are important because they provide some insight into variations from U.S. practice and because they can be used directly to estimate the assets needed to effectively monitor that country.

## Some Remarks On Rockbursts and Nuclear Proliferation

A. McGarr

*U.S. Geological Survey, 345 Middlefield Road, MS/977, Menlo Park, CA 04025-3591*

For three years, starting in early 1986, the U.S. Geological Survey, with support from the Air Force Technical Applications Center, operated a seven-station seismic network in and around the Witwatersrand goldfields, South Africa. I review here three situations related to nonproliferation verification that challenged us to varying degrees.

First, in early October, 1987, the Press Trust of India quoted sources at the Bhabha Research Centre to the effect that a seismic array in the south of India recorded an underground nuclear explosion, on September 30, within South Africa near its border with Mozambique. Within several days of this intriguing event, we obtained the tape from regional station BFT.

The second situation involved a small event, designated 1021030, that occurred on April 12, 1986, in the

Hartebeestfontein mine, 1 km north of station HBF.

The third challenge involves the observation, just mentioned, that the P waves of nearly all tremors recorded at surface stations show downward initial motion. Our understanding of the tremor mechanism changed substantially during the course of analyzing data from three special experiments, each of several weeks duration, involving underground recording beneath stations WDL and HBF. From the exceedingly clear seismograms recorded at depths ranging from 1700 to 3000 m, complete moment tensors could be determined quite precisely. It turns out that, although some tremors show pure normal-faulting mechanisms, the majority entail normal faulting plus an implosive component of comparable magnitude that results in exclusively inward P wave initial motions.

# Blasting Activity of the Mining Industry in the United States

Paul G. Richards

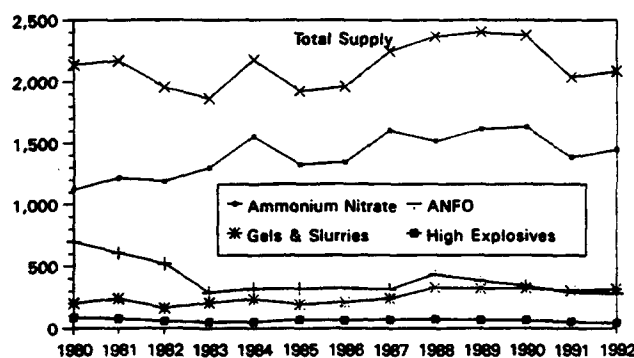
William C. Foster Fellow, U.S. Arms Control and Disarmament Agency/IVI/VC (on leave from Columbia University)

About 2 megatons of chemical explosives are used annually in the U.S., principally in mining for coal and metal ores (Figure 1). Most of this explosive is used in surface mines rather than underground mines. On a typical work day there are about 30 explosions greater than 50 tons, including one shot greater than 200 tons. A few times a year, shots greater than a kiloton are carried out. Shots greater than 100 tons are thought of as large by the blasting industry and occur only at a limited number of mining operations. Shots in underground mines are typically much smaller, because of safety considerations.

Almost all chemical explosions above 1 ton in the U.S. are ripple-fired and shallow. Almost all are intended to break rock or to remove overburden (and are therefore inefficient, relative to contained single shots, in generating seismic signals at regional or teleseismic distances). These attributes, which are not shared with the Non-Proliferation Experiment, are the basis for methods of routinely discriminating most chemical explosions from other seismic sources.

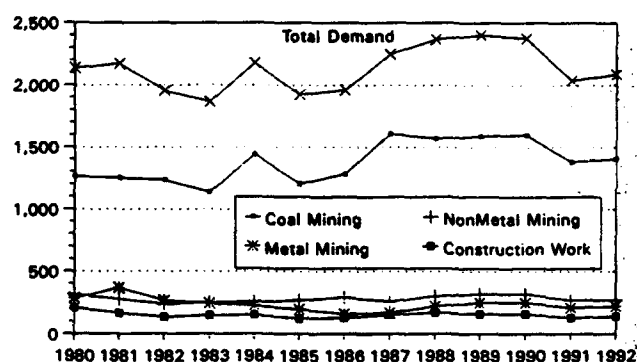
Supply trends U.S. industrial explosives

(Thousand short tons)



Demand trends U.S. industrial explosives

(Thousand short tons)



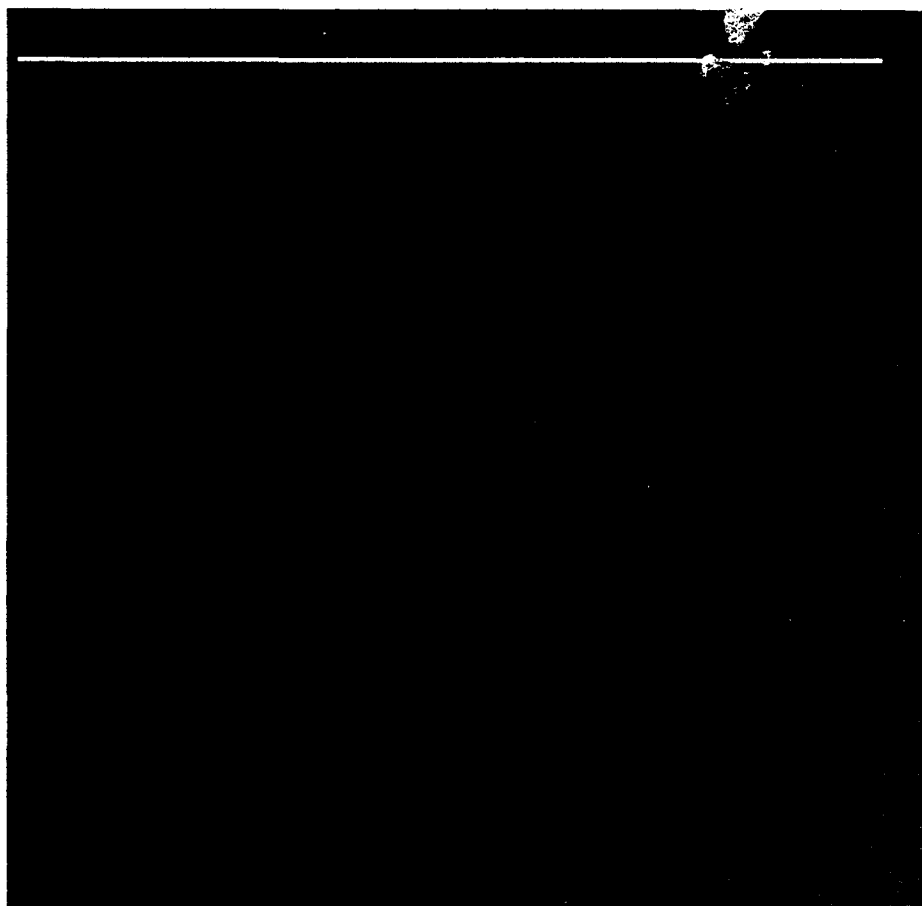
■ Figure 1. Supply and demand of U.S. industrial explosives, 1980-1992 (information from U.S. Bureau of Mines, Department of the Interior).

## Thirty Years of Experience in Treaty Monitoring Applications

*William J. Summa*  
*Defense Nuclear Agency*

Since 1962, the Defense Nuclear Agency has conducted 66 underground nuclear weapons effects tests. Of these 66, 10 were conducted in some form of underground cavity to address a variety of nuclear weapons effects phenomenology. Five additional events were conducted in relatively soft rock, alluvium or tuff, three were conducted in granitic material, one

in dolomite, and one in rhyolite at Amchitka. The unique experience that DNA gained in planning, designing, and executing these tests can provide guidance and support to the U.S. Government in the present multilateral Comprehensive Test Ban discussions in Geneva, Switzerland. Possible applications of these tests will be discussed.



## **Test Preparations**

### **Logistics and Preparations for the NPE**

*Paul J. Thompson and John W. Miller*

*Lawrence Livermore National Laboratory, Nevada Test Site, Mercury, NV*

Logistics and preparations were carried out at the Nevada Test Site for the underground chemical explosion of the Non-Proliferation Experiment. The energy release was detonated with 1.29 million kg of blasting agent using booster charges, each initiated by a high-energy bridge wire detonator. The blasting agent consisted of an ANFO and emulsion mixture. The explosive was emplaced at the end of a newly mined drift that branched off an existing drift in N-Tunnel. Dimensions of the cavity were 15 m in diameter by 4.9 m high; the cavity was instrumented with

arrays of cables, thermocouples, and pressure-measuring instrumentation for scientific and safety monitoring purposes. Instrumentation for the cavity was installed in several tunnel locations external to the tunnel itself and on Rainier Mesa above the detonation point. Remote measurements were made at other locations at the Nevada Test Site and in the southern Sierra Nevada mountain range. This paper will discuss details of the logistics of the experiment and the lessons learned.

## **Lessons Learned as a Result of the NPE**

*Charles McWilliam and Steve Curtis*

*United States Department of Energy, 2753 Highland Avenue, Las Vegas, NV 89109*

The Department of Energy-sponsored Non-Proliferation Experiment (formerly known as the Chemical Kiloton) involved the detonation of blasting agent approximately equivalent to one kiloton of energy release on the Nevada Test Site in an effort to determine whether discriminators exist between conventional and nuclear detonations of similar yield. Coordination among hundreds of scientists from at least 15 different organizations was required to design the experiments necessary to collect and

interpret data from this unique and complex event. Stakeholders and members of the Group of Scientific Experts of the Conference on Disarmament observed the progress of the experiment first hand. The experiment was a success in that a vast majority of the expected data was collected and shared quickly and efficiently throughout the international scientific community. The management of the project is discussed among the major co-sponsoring organizations, and the significant "lessons learned" are presented.

# EOS and Code Simulations

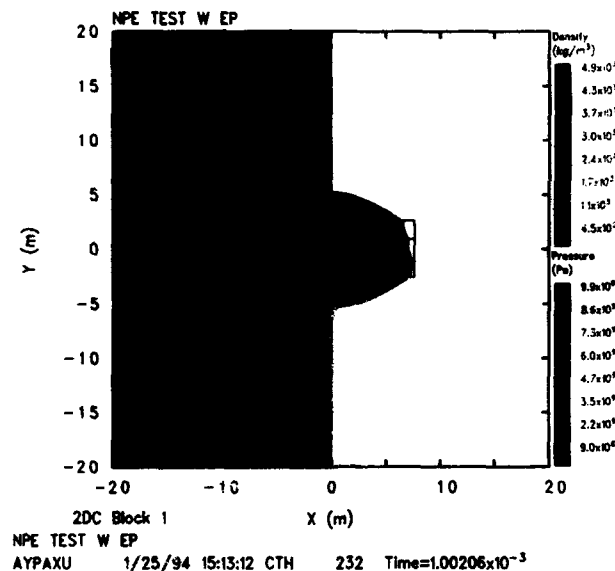
## Modeling the NPE

Randy J. Bos

Los Alamos National Laboratory, Los Alamos, NM

The Non-Proliferation Experiment (NPE) provided the opportunity for modelers to directly compare model predictions for a well-characterized high explosive test and similar-sized nuclear tests in the same media. Because of the high quality of the data, the test also provided the opportunity to upgrade the

saturated tuff equation of state. Model predictions of what we would expect from the difference in a chemical versus a nuclear explosion are discussed. Also discussed is a comparison of model results in the near field and far field with the experimental data.



■ Figure 1. Modeling of the shock wave from the Non-Proliferation Experiment.

# The Influence of Material Models on Chemical or Nuclear Explosion Source-Time Functions

L. A. Glenn and P. Goldstein

*Lawrence Livermore National Laboratory, Livermore, CA*

Physical models of explosion sources are needed to explain the variations in the performance of existing discriminants in different regions, and to help develop more robust methods for identifying underground explosions.

In this paper, we assess the sensitivity of explosion source-time functions to material properties by means of numerical simulations. Specifically, we have calculated the effect of varying the yield strength, overburden pressure, and gas porosity on the spectra of the reduced velocity potential for both nuclear and chemical explosions, and compared these with experimental results derived from free-field particle velocity, local surface velocity, and regional seismic (Livermore-Nevada Test Site Network) data. The chemical-explosion calculations were intended to simulate the kiloton experiment recently conducted in Area 12 of the Nevada Test Site known as the Non-Proliferation Experiment.

We found that the asymptotic (long period) value of the reduced displacement potential,  $\phi_{\infty}$  for

explosions with the ANFO blasting agent used in the NPE, was larger than that derived for a tamped nuclear explosion of the same yield by a factor of 1.9, in good agreement with the experimental results. The absolute values of  $\phi_{\infty}$  also agreed well with those derived via moment-tensor inversion of the seismic data and analysis of the free-field particle velocity measurements. Beyond the corner frequency, the spectra calculated for the chemical and nuclear explosions were indistinguishable, also in good agreement with the experiment. However, the calculated corner frequency was higher than the observed value by a factor of 2 to 3. It was found possible to match the spectral characteristics, but only by assuming unrealistically low material strength for the saturated tuff; when this was done, the values derived for  $\phi_{\infty}$  were high by roughly a factor of 3, in comparison to the moment-tensor inversion results. We discuss plausible reasons for the discrepancy.



## **Background on the Commercial Explosive Chosen for the NPE**

**Mark E. Mammele**  
**DYNO NOBEL, Inc.**

The requirements of the Non-Proliferation Experiment as outlined in the original explosives bid package provided DYNO NOBEL/Alpha-Ireco, Inc., with a unique challenge. The size of the chamber, the total volume of explosives required, the chemical energy equivalent of 1 kiloton, the time-frame of loading the chamber, transportation, and safety were all necessary considerations in choosing this particular explosive. The rationale for choosing this particular

emulsion/ANFO blend of blasting agent explosive will be presented. DYNO NOBEL, Inc., in-house theoretical predictions as to the explosive performance potential of this blasting agent will be compared to some of the actual data acquired upon detonation. The results of this type of experiment may provide new insight as to the efficiency of the energy release of typical commercial explosives.

## **Explosive Performance on the NPE**

*Thomas O. McKown*

*Los Alamos National Laboratory, Los Alamos, NM*

The Explosive Effects Physics Project at the Los Alamos National Laboratory planned and conducted experiments on the Non-Proliferation Experiment (NPE) as part of its effort to define source functions for seismic waves. Since all investigations were contingent on the performance of the emplaced chemical explosive, an array of diagnostic measurements was fielded in the emplaced explosive. The CORRTEX (Continuous Reflectometry for Radius vs Time Experiment) system was used to investigate the explosive initiation and to determine the detonation

velocities on three levels and in a number of radial directions. The CORRTEX experiments fielded in the explosive chamber will be described, including a description of the explosive emplacement from the perspective of its impact on the CORRTEX results. The data obtained are reviewed and the resulting detonation velocities are reported. A variation of detonation velocity with depth in the explosive and the apparent underdetonation and overdetonation of the explosive in different radial directions is reported.

# **Preshot Predictions for the Near-Source Region in the NPE**

*Dan F. Patch, J. Eddie Welch, and James Zerkle*

*SAIC/Simulation Technology Division, 10260 Campus Point Drive, San Diego, CA 92121*

A number of preshot calculations were made in support of the high-explosive Non-Proliferation Experiment at the Nevada Test Site. These calculations addressed a variety of test design, analysis, and construction issues, and sought to identify potential safety concerns.

A series of one-dimensional calculations examined the sensitivity of stress and velocity fields measured near the charge to uncertainties in the high-explosive equation-of-state. This information was needed to properly set gauge ranges for instrumentation fielded near the charge, and to estimate the level of damage that might occur in nearby open tunnels. Additional nuclear source calculations were run to establish a

prediction for the energy equivalence factor for the charge in nearly saturated tuff. This work also provides a measure of the current predictive capability of ground-motion calculations for a familiar and well-characterized medium.

Detailed two-dimensional calculations treated the high-explosive burn and near-source ground-motion phases of the experiment. These calculations examined the extent and evolution of nonisotropic source effects associated with the nonspherical charge geometry and detonation. These effects were of potential concern for close-in stress measurements and of interest in the analysis of far-field data.

## **TIGER Calculations and the NPE Energy Yield**

*P. Clark Souers and Donald B. Larson*

*Lawrence Livermore National Laboratory, Livermore, CA*

Proponents of the Non-Proliferation Experiment (NPE) argue that the critical questions being addressed by this experiment receive definitive answers only if the actual energy yield is known to within 10% and only if there exists a good equation of state description for the explosive. In the case of non-ideal conventional explosives, such as the blasting agent used in the NPE, the explosive will not detonate except in very large diameters and therefore a

determination of the energy of detonation must come from a combination of TIGER code calculations and from measurements made on the experiment itself. The objective in this presentation is to provide the results of an extensive series of TIGER calculations carried out at Lawrence Livermore National Laboratory and to present other material properties information, all of which are pertinent to a proper description of the NPE explosive.

## ***Rainier Mesa Structure***

### **Geologic Characteristics of the NPE Site in the U12n.25 Drift of N-Tunnel, Nevada Test Site**

*M. J. Baldwin, R. P. Bradford, S. P. Hopkins, and D. R. Townsend  
Raytheon Services Nevada, P. O. Box 328, Mercury, NV 89023*

*B. L. Harris-West  
Defense Nuclear Agency, P. O. Box 208, Mercury, NV 89023*

The Nuclear Non-Proliferation Experiment was conducted in the U12n.25 drift in N-Tunnel at the Nevada Test Site. The geologic characterization of the site was performed by Raytheon Services Nevada geologists in a standard manner developed for all underground nuclear weapons-effects tests executed by the Defense Nuclear Agency.

The U12n.25 test bed was constructed in zeolitized ash-fall tuff of the Tunnel Beds Tuff, Subunit 4K, 389.0 m below the surface of Rainier Mesa. The structural geology of the site was simple, with the nearest fault plane projected to be 11 m below the mined cavity at closest approach and an average

bedding dip of 7 degrees to the northwest. The cavity excavation revealed several small fractures, including one that produced minor amounts of free water during construction. The physical properties of the site were well within the range of experience for the zeolitized tuff of N-Tunnel, and no geology-related problems were encountered during construction.

The zeolitized tuff of N-Tunnel has been the site of 20 nuclear tests conducted by the Defense Nuclear Agency. The similarities of geologic setting, site geometry, and physical properties allow many comparisons of Non-Proliferation Experiment results with the large nuclear-test data base.

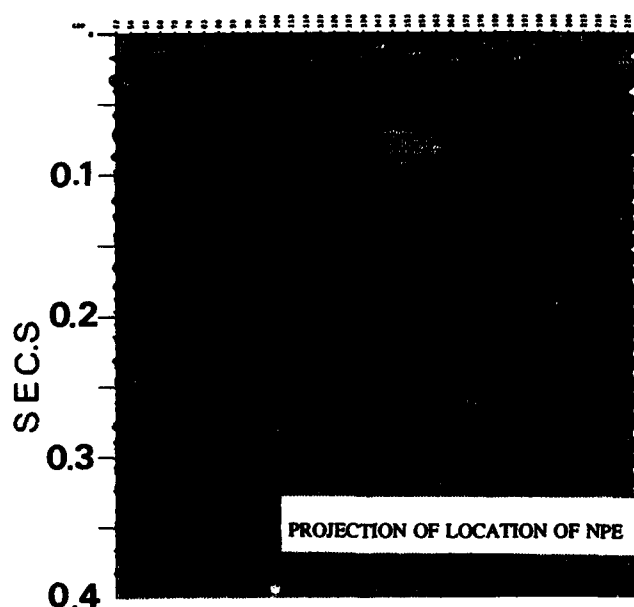
# High-Resolution Seismic Imaging of Rainier Mesa Using Surface Reflection and Surface-to-Tunnel Tomography

E. L. Majer, L. R. Johnson, E. K. Karageorgi, and J. E. Peterson

Center for Computational Seismology, Lawrence Berkeley Laboratory, Berkeley, California 94720

In August 1993, two high-resolution seismic experiments were carried out in N-Tunnel and on the surface above N-Tunnel. In the tunnel extending south toward Misty Echo, 96 30-Hz geophones were placed at 3-m increments along the wall of the tunnel and connected to a 96-channel high-resolution Bison model 90-96 seismograph. After the geophones were deployed, a Bison EW-4 impact source was used at the surface of the mesa to provide an energy source for the surface-to-tunnel tomographic imaging experiment. The source was used at 15-m increments along a line approximately parallel to the tunnel as

shown in Figure 1. In a separate experiment, a high-resolution reflection line was also carried out in order to image the lithology above and possibly below the Non-Proliferation Experiment explosion. Due to overwhelming 60-hertz noise in the tunnel, limited data were acquired for the tomography experiment and a full image was not possible. The reflection results, however, revealed good images of the layering in Rainier Mesa. Also shown in Figure 1 is a migrated image from the reflection line. The strong near-surface reflector is assumed to be a Basaltic flow, and the deeper reflectors are within the Tuff.



■ Figure 1. The location of the surface reflection line relative to the explosion and a migrated section from the reflection data.

# ***NPE Source Parameters from Freefield Ground-Motion Measurements***

## **Freefield Seismic Ground Motion on the NPE**

*H. Douglas Garbin*

*Sandia National Laboratories, Dept. 9311, Albuquerque, NM*

In addition to a number of stress and acceleration measurements made in the inelastic regime for the NPE, Sandia fielded two tri-axial accelerometer packages in the seismic free field. The gauges were located at ranges near 200 m on the opposite sides of a vertical fault. This location allowed us to assess several different aspects related to nonproliferation. Comparisons are made with nuclear tests to estimate yield, calculate seismic energy release, and detect spectral differences between nuclear and non-nuclear explosions. The results show the conventional

explosion couples to the medium much better at low frequencies than do nuclear explosions, and that nuclear explosions contain more high-frequency energy than the NPE. The data is inconclusive on whether the fault had relative vertical motion. The radial components of the two packages show similar motion although there are several nonseismic glitches in the time series. This causes difficulty in integrating for the displacement or reduced displacement potential.

# Comparison of Chemical and Nuclear Explosion Source-Time Functions from Close-in, Local, and Regional Seismic Data

Peter Goldstein and Stephen P. Jarpe

Lawrence Livermore National Laboratory, Livermore, CA

The primary goals of this study are to address two questions: (1) can large chemical explosions be discriminated from nuclear explosions, and (2) can large chemical explosions be used to calibrate regions of interest for improved event identification? The answers to these questions have important implications for the verifiability of a Comprehensive Test Ban Treaty and the utility of seismic measurements for confidence building.

A key technical issue for discrimination of and calibration with chemical explosions is the identification of similarities and differences between chemical and nuclear explosion sources and the signals they produce. With this in mind, we compare close-in, local, and regional estimates of source-time functions and source spectra of the Non-Proliferation Experiment (NPE), a 1-kiloton chemical explosion in N-Tunnel at

Rainier Mesa on the Nevada Test Site, with those of nearby nuclear explosions.

Based on close-in and local measurements of the NPE, we find that the asymptotic (long-period) value of the scaled reduced displacement potential,  $\phi_{\infty}$ , is approximately twice as large as that of nearby nuclear explosions. We also find that the scaled corner frequency of the NPE is lower than that of nearby nuclear explosions. However, when the data are scaled to the same moment (equal, low-frequency spectral levels) the spectra are almost indistinguishable.

In a monitoring environment where yield would not be known, it is unlikely that such differences could be used for discrimination. In contrast, these measurements suggest that chemical explosions may be useful for calibrating a region for discrimination between explosions and earthquakes.

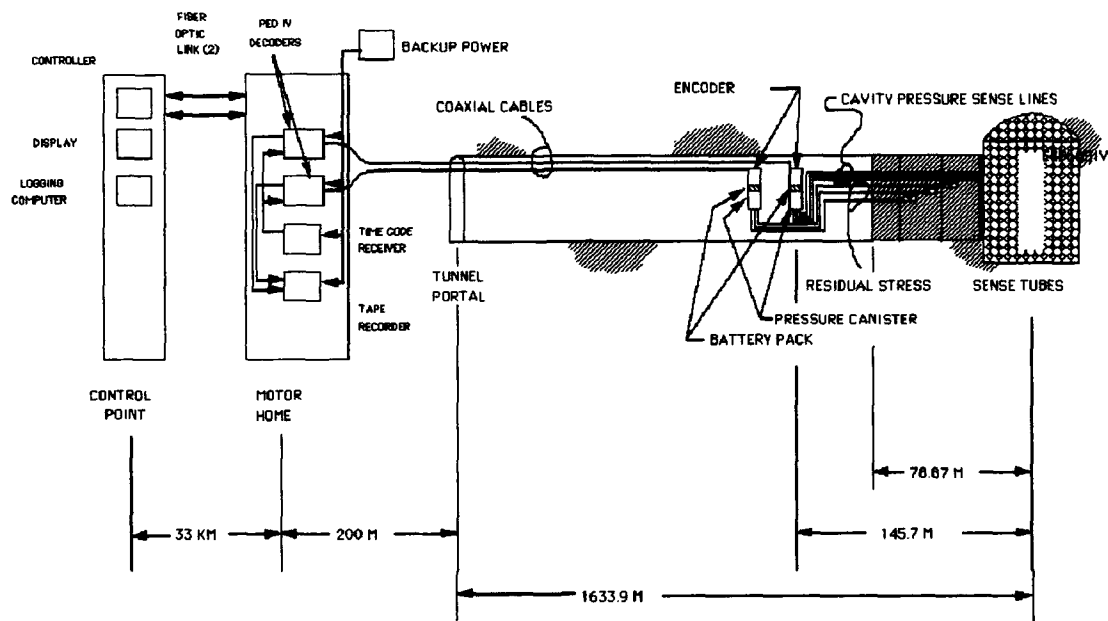


# Cavity Pressure/Residual Stress Measurements from the NPE

Raymond A. Heinle and Billy C. Hudson  
Lawrence Livermore National Laboratory  
Melton A. Hatch, Jr.  
EG&G Energy Measurements, Mercury, NV

The Lawrence Livermore National Laboratory planned and conducted experiments on the Non-Proliferation Experiment to determine post-detonation gas pressure inside the explosive cavity and the residual rock stress in the region immediately outside the cavity. Before detonation there was significant concern that steam and explosive detonation products would create very high temperatures and pressure in the blast cavity that would exist for weeks and months after firing. This could constitute a safety hazard to personnel re-entering the tunnel. Consequently,

the Lawrence Livermore National Laboratory was asked to field its Cavity Pressure/Residual stress monitor system on the Non-Proliferation Experiment (Figure 1). We obtained experimental data for the first 600 ms after the explosion and again several weeks after detonation upon tunnel re-entry. We recorded early-time cavity pressure of about 8.3 MPa. In addition we believe that the ends of our sensor hoses were subjected to an ambient driving pressure of about 0.5 MPa that persisted until at least one month after zero time.



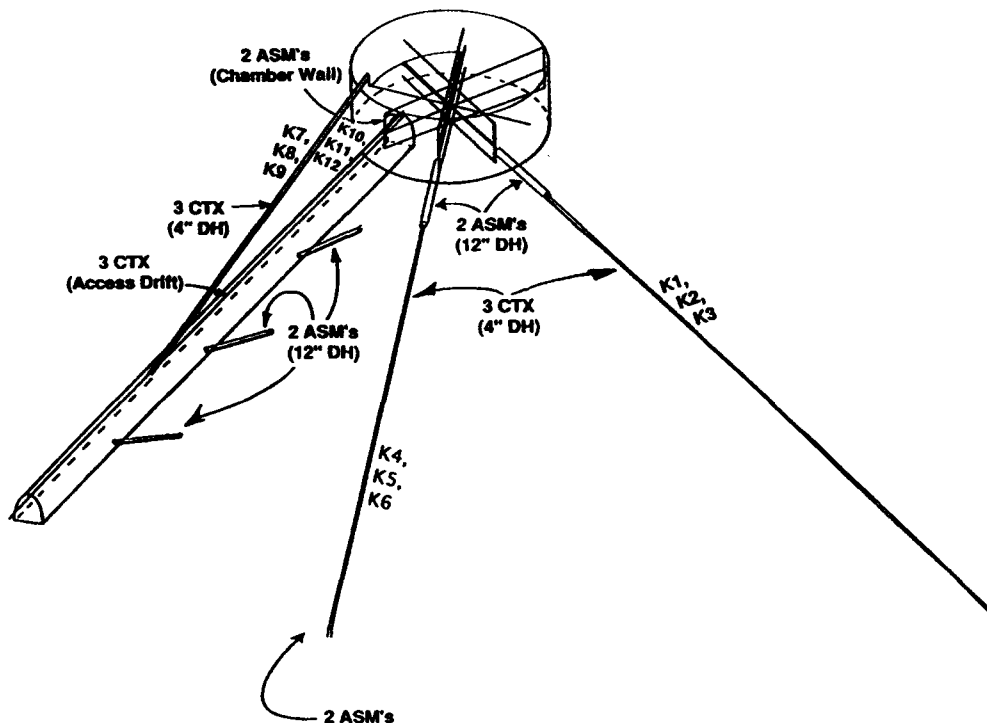
■ Figure 1. The NPE cavity pressure and residual stress decay experimental equipment that measured pressure in the explosive cavity.

# Induced Shock Propagation from the NPE

Thomas O. McKown  
Los Alamos National Laboratory

The Explosive Effects Physics Project at the Los Alamos National Laboratory planned and conducted experiments on the NPE as part of its effort to define source functions for seismic waves. Beyond the explosion chamber, the detonation-induced shock propagated through the saturated tuff of the N-Tunnel complex. The CORRTEx (Continuous Reflectometry

for Radius vs Time EXperiment) system was used to investigate the shock propagation in two drill holes and the access drift (Figure 1). The CORRTEx experiments will be described. The data are reviewed, and an apparent asymmetry in the radiating shock is discussed.



■ Figure 1. CORRTEx instrumentation plan on the Non-Proliferation Experiment.

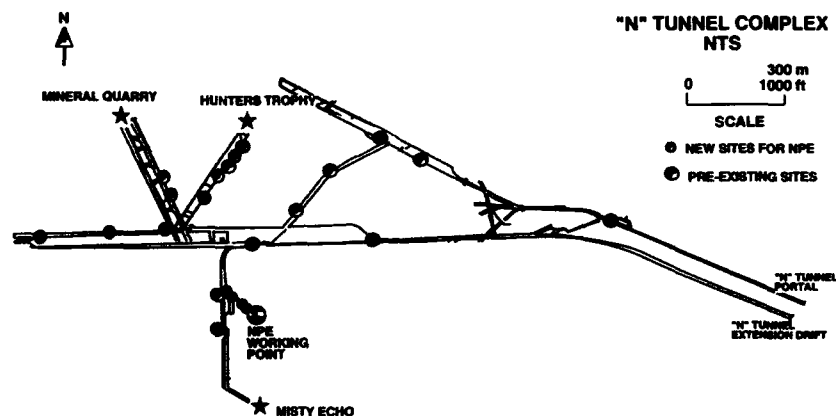
# Freefield Ground Motions from the NPE: Preliminary Comparisons with Nearby Nuclear Events

Kenneth H. Olsen and Anthony L. Peratt

Explosion Effects Physics Project, Group P-15, Los Alamos National Laboratory, Los Alamos, NM 87545

Since 1987, in an effort to provide more extensive close-in (<10 km) data sets for modern regional and teleseismic source-function studies, we have installed fixed arrays of tri-axial accelerometers in the free field near the shot horizons for low-yield ( $\leq 20$  kt) nuclear events in the N-Tunnel complex beneath Rainier Mesa. For the Non-Proliferation Experiment (NPE) we augmented the array to achieve 23 freefield stations (Figure 1). Our accelerometer arrays span distance intervals between the nonlinear material failure region—where peak stresses are the same order as rock strengths (<100 kilobars and ranges typically ~50–150 m)—and distances (~1 km) where linear-elastic response is expected (stress <50 bars; accelerations <1 g). Goals are: (a) to examine robustness and stability of various freefield source function estimates, *e.g.*, reduced displacement potentials and spectra; (b) to compare close-in with regional estimates to test whether detailed close-in freefield and/or surface ground motion data can improve predictability of regional-teleseismic source functions;

and (c) to provide experimental data for checking two-dimensional numerical simulations. We report preliminary comparisons between experimental freefield data for the NPE (1993) and three nearby nuclear events (Misty Echo, 1988; Mineral Quarry, 1990; Hunters Trophy, 1992). All four working points are within 1 km of each other in the same wet tuff bed, thus minimizing concerns about possible large differences in material properties between widely separated experiments. Initial comparison of acceleration and velocity seismograms for the four events reveals: (1) there is a large departure from spherical symmetry commonly assumed in analytic treatments of source theory; vertical components are significant, (2) all experiments show similar peak particle velocity amplitude decay rates  $\sim R^{-1.8}$ , suggesting significant attenuation even in the supposedly purely elastic region, and (3) no sharp arrivals are resolvable at tunnel level from near-surface pP reflections or spall-closure sources.



■ Figure 1. Free-field accelerometer array for the Non-Proliferation Experiment.

## **NPE Close-In Stress and Motion Measurements**

**Carl Smith**

*Sandia National Laboratories, Post Office Box 5800, Albuquerque, New Mexico 87185-1159*

On the Non-Proliferation Experiment, we measured freefield radial stress to document the evolution of the shock wave to a quasi-elastic wave and to provide data for a comparison with calculations of the process. We also measured hoop stress and acceleration in the free field, and radial stress and acceleration in the stemmed drift. Measured stress waveforms show significantly more amplitude than scaled

waveforms from nearby nuclear events. Specifically, the five stress peaks suggest an equivalent nuclear yield of at least two kilotons. Motion data from integrated acceleration also show an enhancement. Nonradial accelerations show some departure from spherical symmetry. Tuff strengths (inferred from differences between radial and hoop stresses) show values of 0.7 to 0.9 kilobars.

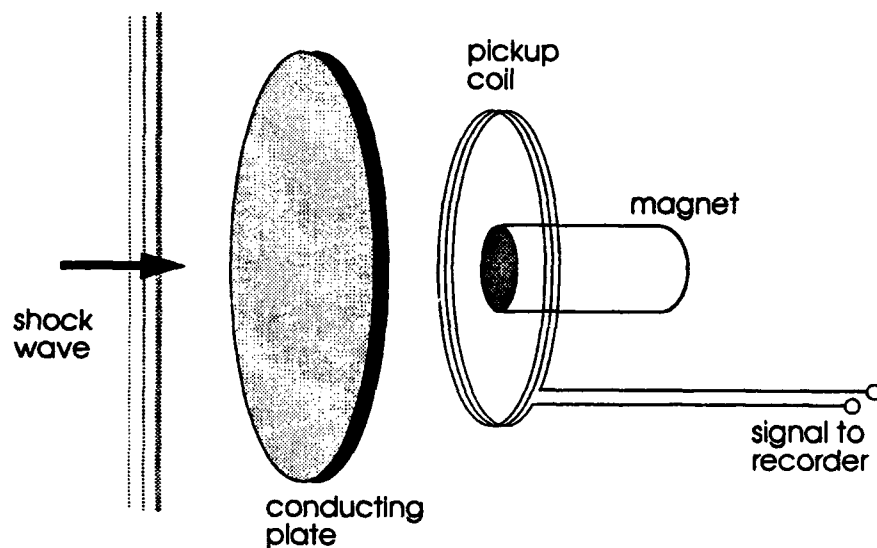
# Axisymmetric Magnetic Gauges

B. L. Wright, K. R. Alrick, and J. N. Fritz

Los Alamos National Laboratory, Los Alamos, NM 87545

Axisymmetric magnetic (ASM) gauges are useful diagnostics tools in the study of the conversion of energy from underground explosions to distant seismic signals. Requiring no external power, they measure the strength (particle velocity) of the emerging shock wave under conditions that would destroy most instrumentation. Shock pins are included with each gauge to determine the angle of the shock front. For the Non-Proliferation Experiment, two ASM gauges were installed in the ANFO mixture to monitor the

detonation wave and ten were grouted into boreholes at various ranges in the surrounding rock (10 to 64 m from the center of the explosion; Figure 1). These gauges were of a standard 4-inch-diameter design. In addition, two unique jumbo ASM gauges (3-ft by 3-ft in cross section) were grouted to the wall of a drift at a range of 65 m. We discuss issues encountered in data analysis, present the results of our measurements, and compare these results with those of model simulations of the experiment.



■ Figure 1. The ASM gauge approach to measuring shocked material motion. For the NPE event, ASM gauges were installed in the ANFO mixture and in the surrounding rock to a range of 65 m.

# NPE Source Parameters from Local Seismic Measurements

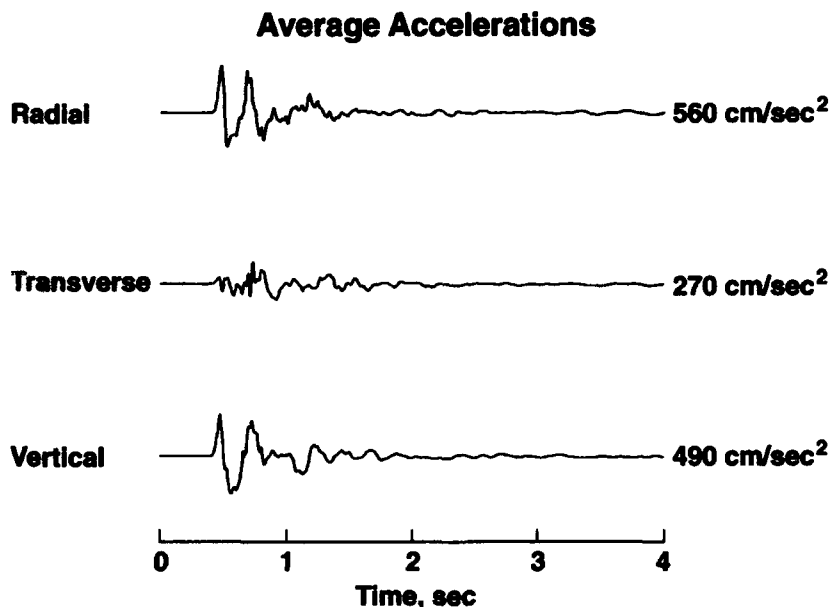
## Recording Experiment on Rainier Mesa in Conjunction with a Reflection Survey

Lane R. Johnson

Seismographic Stations, University of California, and Center for Computational Seismology, Lawrence Berkeley Laboratory, Berkeley, California 94720

The chemical explosion of the Non-Proliferation Experiment was recorded on the surface of Rainier Mesa along the same line that had previously been the site of a high-resolution reflection survey. Six three-component accelerometer stations were distributed along the 550-meter line, which was offset about 600 meters from the epicenter of the explosion. The bandwidth of the acceleration data extends to 100 Hz. Even though the separation of the stations was only about 100 meters, the waveforms and the amplitudes exhibited considerable variability, especially for the transverse component of motion.

The maximum accelerations ranged between 0.27 g and 1.46 g, with the maximums of the average traces being 0.57 g on the radial component, 0.28 g on the transverse component, and 0.50 g on the vertical component (Figure 1). Using the results of the reflection survey to help constrain the velocity model, the acceleration data are being inverted to obtain estimates of the seismic source parameters. The data are also being processed as a seismic array in order to estimate the coherence and mode of propagation for various parts of the wave train.



■ Figure 1. The average accelerations that were observed at the six stations for the radial, transverse, and vertical components of motion. The maximum accelerations are shown at the end of each trace.

# **Near-Source Surface Seismic Measurements for the NPE**

*Robert E. Reinke and Al Leverette*

*Field Command Defense Nuclear Agency/FCTTS, Kirtland AFB, NM 87117*

*Brian W. Stump, D. Craig Pearson, and C. L. Edwards*

*Los Alamos National Laboratory, EES-3, MS-C335, Los Alamos, NM 87545*

An extensive seismic network was deployed on the surface of Rainier Mesa for both the Non-Proliferation (NPE) Calibration shot and full-scale NPE event. This network was very similar to previous deployments for the nuclear events Misty Echo, Mineral Quarry, and Hunters Trophy. For the full-scale NPE event, three-component accelerometers and seismometers were fielded at 32 sites across the mesa. A slightly smaller network with 28 stations was in operation for the 136-kg NPE Calibration event. The mesa-top network included both accelerometers and seismometers. The

accelerometers were used to obtain data from the main NPE event, while the seismometers with their higher sensitivity were used to record the 136-kg calibration shot and several hundred after-events from the NPE. Large spatial variations in ground motions are evident in both the full mesa data set and in a small-aperture (80 m on a side), nine-element triangular array. This paper summarizes the data and discusses wave propagation effects. A companion paper presents a comparative source analysis.

# Relative Source Comparison of the NPE to Underground Nuclear Explosions at Local Distances

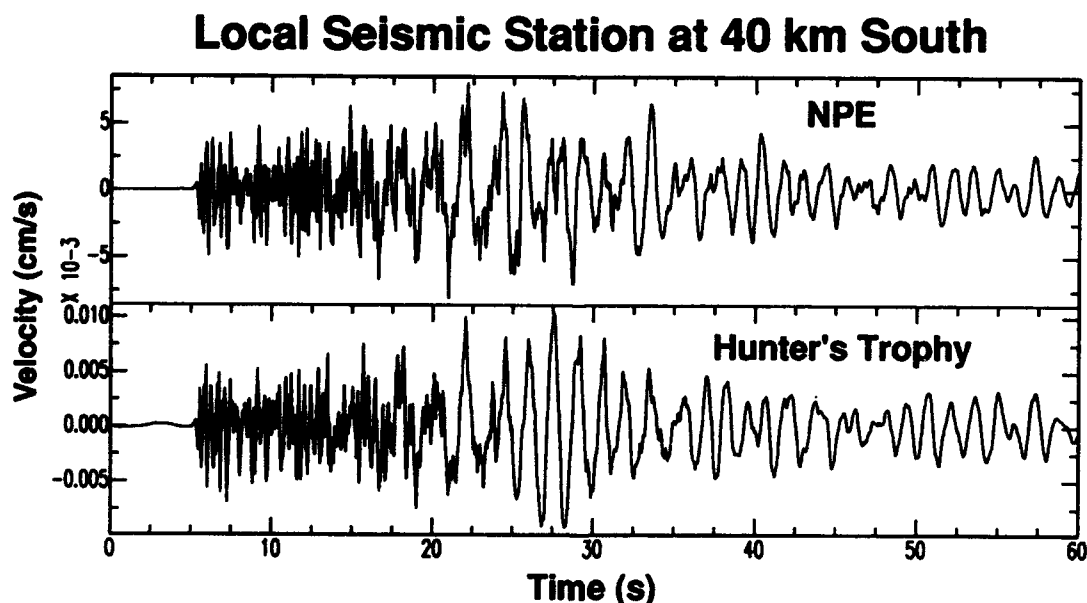
Albert T. Smith

Lawrence Livermore National Laboratory, Livermore, CA

The NPE provides an opportunity to compare broadband characteristics of chemical to nuclear explosions at a group of local stations (4 to 40 km distant). The locations for these stations were established on bedrock to record Millyard, a small partially decoupled nuclear explosion, Diamond Beech, and Hunters Trophy, all shots within N-Tunnel on Rainier Mesa, Area 12. These sites were also occupied to record aftershocks from the Little Skull Mountain earthquake and chemical explosions from the USGS Sierra Experiment. To minimize calibration errors during this

period, redundant instrumentation plus similar types were used for each event.

The analysis emphasizes the source characteristics of the different explosions. The 136-kg chemical calibration explosion allows removal of path effects from each explosion. The NPE and Hunters Trophy produced very similar waveforms (Figure 1). The Millyard nuclear explosion and the chemical calibration explosion show higher frequency content, consistent with a higher corner frequency for the sources.



■ Figure 1. Local seismic station at 40 km south of Rainier Mesa.



# Analysis and Interpretation of Free-Surface Ground Motions from the NPE

*Brian W. Stump, D. Craig Pearson, and C. L. Edwards*

*Los Alamos National Laboratory, EES-3, MS-C335, Los Alamos, NM 87545*

*Robert E. Reinke*

*Field Command Defense Nuclear Agency/FCTTS, Kirtland AFB, NM 87117*

Velocity and acceleration signals were recovered from as many as 32 stations on Rainier Mesa for each of the nuclear explosions Misty Echo, Mineral Quarry, and Hunters Trophy, and the chemical explosions NPE and NPE Calibration. The same receiver sites were used for the different explosions. These data and the quantification of the wave propagation effects are summarized in a separate abstract (see page 47). The waveforms reflect strong, repeatable receiver effects as exemplified by a factor of 3 to 6 scatter in peak accelerations across the network from the same explosion.

Two different approaches are pursued in this comparative source analysis, both of which account for local propagation path effects. The first involves empirical comparisons between the different events

assuming similar propagation path effects for each source to a given receiver. Both frequency and time domain comparisons are made. Spectral comparisons between Hunters Trophy and the NPE at common receivers indicate that within the bandwidth of the data (0.4–100 Hz) the long-period level, corner frequency, and high frequency decay are nearly identical. Comparisons of data between the NPE and NPE Calibration explosions are dominated by the nearly four orders of magnitude difference in spectral levels. The second source analysis technique is a parametric fit of an explosion source model to the data with an appropriate propagation path correction. These inversions suggest that trade-offs between long-period level, corner frequency, and source overshoot exist as a result of the data bandwidth.

## ***Regional Seismic Results***

### **A Comparison of NPE and Misty Echo, Mineral Quarry, and Hunters Trophy**

*William Summa*  
*Defense Nuclear Agency*

The Non-Proliferation Experiment was conducted by Lawrence Livermore National Laboratory on September 22, 1993, in the N-Tunnel complex of Area 12 at the Nevada Test Site. This experiment had an energy release of approximately 1 kiloton. Directly related to the analysis of this experiment in the same region of N-Tunnel are three DNA underground tests: Misty Echo (12/10/88), Mineral Quarry (7/25/90), and Hunters Trophy (9/18/92).

The first of the three events, Misty Echo, was conducted in an 11-m hemispherical cavity. The second

and third, Mineral Quarry and Hunters Trophy, were horizontal line-of-sight tests. A good understanding of the past data from N-Tunnel and the explosion-point geometry is important for the community to make a comparison with the NPE. For example, Mineral Quarry had a very complex set of add-on experiments at the explosion point. A description of each configuration and the relevant close-in source ground motion data will be discussed in terms of range-scaled parameters to provide nuclear test background for the NPE presentations that follow.

## **NPE Yield from Leo Brady Seismic Network**

*H. Douglas Garbin*

*Sandia National Laboratories, Dept. 9311, Albuquerque, NM*

The Leo Brady Seismic Net (LBSN) has been used to estimate seismic yields on U.S. tests for over 30 years. One of the concerns of the Non-Proliferation Experiment (NPE) was the yield equivalence between a large conventional explosion and a nuclear explosion. Because of the experience we have built up in measuring yields, the five-station net that surrounds the Nevada Test Site was put into its normal explosion

operation to record NPE signals. Comparisons were made with nine nuclear tests within an 800-m range of the NPE source and resulted in yields per test ranging from 1.3 to 2.2 kt. Using the same techniques in determining nuclear explosion yields, the 1-kt NPE measured at 1.6-kt nuclear-equivalent yield with a standard deviation of 16%.

# Separation of Source and Propagation Effects at Regional Distances

*Peter Goldstein, Steve Jarpe, Kevin Mayeda, and William R. Walter  
Lawrence Livermore National Laboratory, Livermore, CA*

Improved estimates of propagation effects are needed to explain the performance of existing discriminants and to help develop more robust methods for identifying underground explosions.

In this paper, we use close-in and local estimates of explosion source-time functions to remove source effects from regional recordings of the Non-Proliferation Experiment (NPE), a 1-kiloton chemical explosion in N-Tunnel at Rainier Mesa on the Nevada Test Site, and nearby nuclear explosions. Using these events as a source array, we plot source corrected

waveforms in record section format in an attempt to separate regional propagation effects from near-source scattering effects. Source-corrected Pn, Pg, Lg, and coda spectra are used to estimate the effects of attenuation.

Our preliminary analysis of waveforms from closely spaced events indicates significant waveform variability that is probably due to near-source scattering. We also find significant differences in the effects of attenuation for the Pn, Pg, Lg, and coda phases.

# Dynamic Bayesian Filtering for Real-Time Seismic Analyses

*David K. Blough, Alan C. Rohay, Kevin K. Anderson  
Pacific Northwest Laboratory, Richland, WA*

State space modeling techniques, such as the Kalman Filter, have been used to analyze many non-stationary time series. The ability of these dynamic models to adapt and track changes in the underlying process makes them attractive for application to the real-time analysis of three-component seismic waveforms. We are investigating the application of Bayesian filtering techniques to phase detection, polarization, and spectrogram estimation.

This approach removes the need to select data windows from the time series prior to spectrum

estimation. We expect to use the filtering approach to isolate particular seismic phases based upon polarization parameters that are determined at a spectrum of frequencies, and to utilize these spectra directly in discriminating between different seismic source types.

The methods are illustrated on the Non-Proliferation Experiment, nuclear tests and earthquakes from the Nevada Test Site using data from the Lawrence Livermore National Laboratory's regional stations.

# **Investigations of the Low-Frequency Seismic Waves Recorded at Near-Regional Distances from the NPE**

*Howard J. Patton*

*Lawrence Livermore National Laboratory, Livermore, CA*

A major objective of the Non-Proliferation Experiment (NPE) is to understand source coupling of chemical explosions in the context of our experience with nuclear explosions at the Nevada Test Site. Reported differences between the level of Rayleigh-wave excitation for the NPE and nearby Rainier nuclear shots was the motivation for this study, which also focused attention on coupling at low frequencies,  $<0.2$  Hz. Unfortunately, the signal-to-noise ratio (S/N) is poor at most regional stations in this frequency

range. To improve the S/N for the NPE, a stacking method has been employed which equalizes surface waves for differences in their propagation paths. The resulting stacked seismogram is an estimate of the low-frequency wavefield based on stations at many different azimuths, thus averaging out asymmetries that may be present in the source. This result will be used to estimate the seismic moment of the NPE and for comparisons with the low-frequency coupling of nuclear tests.

# Lawrence Livermore National Laboratory Seismic Yield Determination for the NPE

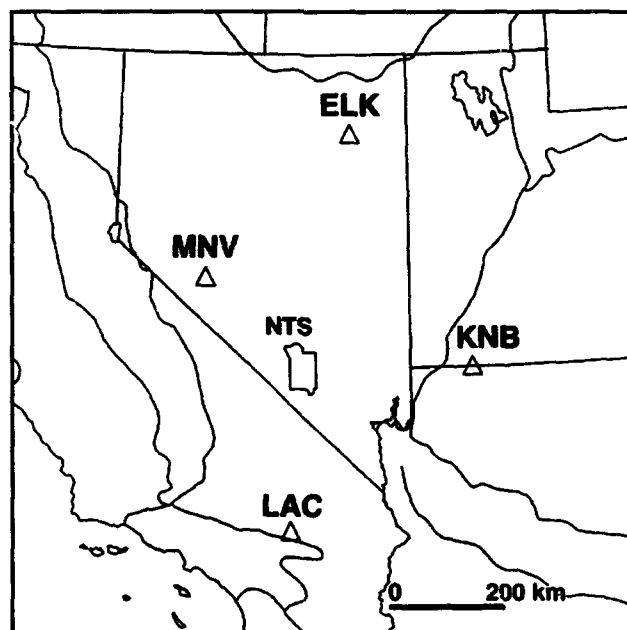
Robert Rohrer

Lawrence Livermore National Laboratory, Livermore, CA

Lawrence Livermore National Laboratory recorded seismic signals from the Non-Proliferation Experiment at the Nevada test site on September 22, 1993, at seismic stations near Mina, Nevada; Kanab, Utah; Landers, California; and Elko, Nevada (Figure 1).

Yields were calculated from these recorded seismic amplitudes at the stations using statistical

amplitude-yield regression curves from earlier nuclear experiments performed near the Non-Proliferation Experiment. The weighted seismic yield average using these amplitudes is 1.9 kt. The calibrating experiments were nuclear so this yield is equivalent to a 1.9-kt nuclear experiment. The estimated accuracy of this yield determination is  $\pm 17\%$ .



■ Figure 1. Location of the Mina, Kanab, Landers, and Elko LLNL seismic stations recording signals from the NPE.

# The NPE Recorded at the Pinedale Seismic Research Facility

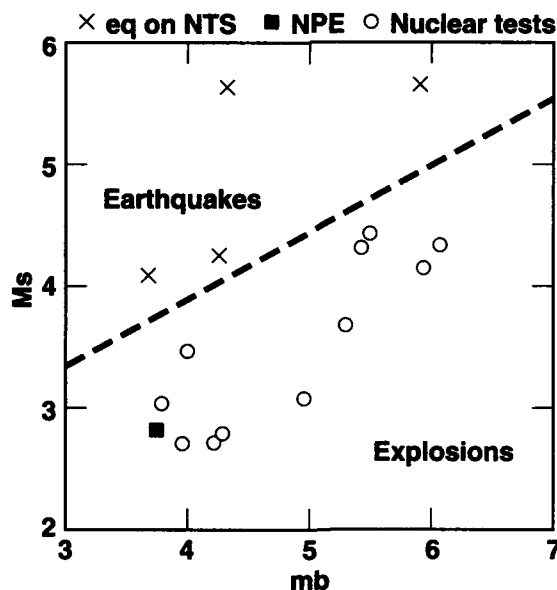
Dorthe B. Carr

Sandia National Laboratories, Albuquerque, NM 87185-0655

The Non-Proliferation Experiment was recorded by five different seismic stations operated by Sandia National Laboratories at the Pinedale Seismic Research Facility, approximately 7.6° from the Nevada Test Site. Two stations are different versions of the Deployable Seismic Verification System developed by the Department of Energy to provide seismic data to verify compliance with a Comprehensive Test Ban Treaty. Vault and borehole versions of the Designated Seismic Stations also recorded the event. The final station is test instrumentation (GS-28) located at a depth of about 400 m. Although the event is seen clearly at all the stations, there are variations

in the raw data due to the different bandwidths and depths of deployment. The deep borehole instrument had the lowest noise.

One Deployable Seismic Verification System has been operating for over three years and in that time recorded 14 nuclear explosions and 4 earthquakes from the Nevada Test Site. Several discriminants have been applied to this data. The best results are with the  $m_b$ - $M_s$  discriminant, which shows clear separation between the earthquakes and nuclear explosions (Figure 1). At this regional distance and test site, this chemical explosion is indistinguishable from a nuclear explosion.



■ Figure 1. The  $m_b$ - $M_s$  discriminant for the Deployable Seismic Verification System located 7.6° from the Nevada Test Site. There is good separation between NTS explosions and earthquakes occurring on the Test Site. The Non-Proliferation Experiment clearly falls in with the nuclear explosions.



# Southern Sierras Continental Dynamics Project: NPE Observations Across the Sierra Nevada

P. E. Malin

Department of Geology, Box 90235, Duke University, Durham, NC 27708, and US SSCD Working Group

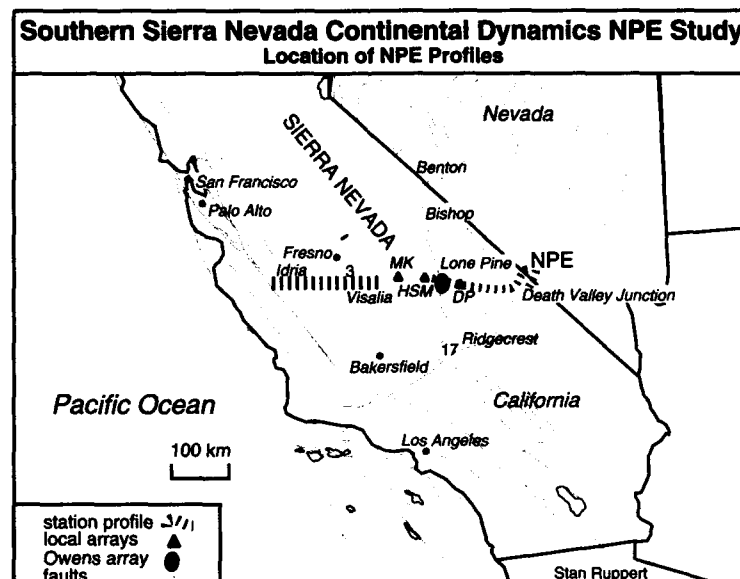
D. Jongmans

L.G.I.H., Liege University, Bat. B19, 4000 Liege, Belgium, and NATO SSCD Working Group

The Southern Sierras Continental Dynamics (SSCD) Project fielded some 350 portable seismic recorders for the Non-Proliferation Experiment (NPE). The stations were equipped with three-component and vertical geophones, with both short-period and broad-band responses. The various sensors were interleaved to give: (a) a 450-km profile across the Sierras at 2-km station spacings and (b) local arrays placed both in a circle around Owens Lake and in three smaller apertures, at Darwin Plateau, Horse Shoe Meadow, and Mineral King (Figure 1). The arrays and 25 of the profile stations were also used to record earthquakes for several weeks. These events

include a magnitude 3+ Death Valley event and the 5+ event in Oregon.

The SSCD NPE data are part of a major seismic profiling effort. It includes two 350-km refraction lines, one along Owens Valley and one across the Sierras, from Death Valley to the San Andreas fault. The data were distributed to the SSCD members in February 1994. The data show that while the Sierras do not appear to have a major crustal root, longer-period Lg-type waves are clearly affected by them. We are combining these observations into a model of seismic wave propagations across batholiths for both scientific and nuclear discrimination purposes.



■ Figure 1. Locations of of NPE profiles.

## Lg Coda Spectral Ratios of the NPE

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Spectral ratios of the Non-Proliferation Experiment (NPE) were taken from recordings using the Livermore Nevada Test Site Network (LNN) at distances of 200–400 km. Lg coda ratios of the NPE were compared against those of nuclear explosions and earthquakes from the Nevada Test Site (NTS). Using a ratio comparing amplitudes between 1–2 Hz and 8–10 Hz, we found that in general Rainier Mesa events (Area 12) of roughly the same yield had significantly lower spectral ratios than those from Yucca

Flats. Both the NPE and Hunters Trophy exhibited the smallest ratios from Area 12, falling within the earthquake population. Lg coda source spectra for these two events show very shallow fall-offs above the corner frequency, remarkably similar to after-shocks of the Little Skull Mountain earthquake of June 29, 1992. In addition, ratios from recent shallow earthquakes from Rock Valley at NTS appear to be intermediate between the Little Skull Mountain after-shocks and nuclear explosions.

# **NPE and Nuclear Effects of Travel Distance and Site Geology on Regional Discriminants along a Seismic Profile in Northwest Nevada**

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*Keith Priestley*

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To address questions of discriminant transportability, it is important to understand how discriminants are affected by regional phase propagation and site geology. To examine this issue, we have recorded the Non-Proliferation Experiment (NPE) at nine sites on a 250-km-long profile through western Nevada, along which the crustal structure has been well studied. This study uses these data to investigate the stability and variation of a number of proposed seismic discriminants and compares these with

observations at permanent regional stations belonging to the Livermore NTS Network from the work of Walter and others. The preliminary measurements of the spectral ratios (1 Hz/6 Hz) along the profile are stable for Lg but more variable for Pn and Pg. The amplitude ratio for Pg/Lg is reasonably stable with distance but the ratio for Pn/Lg decays with distance. A nuclear explosion has previously been recorded along the same profile, and will be analyzed and contrasted with the NPE results.

## **Southern Sierra Nevada Continental Dynamics Project: 1993 Field Observations and Interpretations of 24 Shots and NPE**

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*Randy Keller*

*University of Texas at El Paso*

*Peter Malin*

*Duke University and the Southern Sierra Nevada Continental Dynamics Working Group*

The Southern Sierra Nevada Continental Dynamics Project is a multidisciplinary, multi-institutional investigation of the cause of the uplift of the Sierra Nevada and its relationship to extension in the adjacent Basin and Range. A broad range of geologic and geophysical data have been collected as part of this project. These data include both passive and active seismic, gravity, and magnetotelluric. Three seismic refraction/wide-angle reflection profiles were recorded: (1) a 325-km-long, north-south profile extending from just east of Mono Lake south across the Garlock fault, (2) a 400-km-long, east-west profile extending from Death Valley west across the Sierra Nevada Mountains to the San Andreas Fault, and (3) a 480-km-long, east-west profile for the NPE

extending from Beatty, Nevada, west across the Sierra Nevada along the previously recorded east-west profile, continuing nearly to the Pacific Ocean. Up to 675 seismic recorders were deployed for each profile. These data have allowed us to develop refined models of the crustal and upper mantle structure of the southern Sierra Nevada and to evaluate alternative hypotheses for its uplift and for Basin and Range extension.

(The Working Group includes representatives from Duke Univ., Caltech, Univ. Nevada-Reno, Princeton, U.C. Riverside, Univ. of Texas at El Paso, San Diego State Univ., Stanford Univ., China Lake Naval Weapons Center, and the U.S. Geological Survey.)

# A Broadband Seismic Profile of the NPE

T. C. Wallace, M. Tinker, S. Myers, J. Swenson, R. Brazier, G. Fan, and S. Beck  
SASO, Department of Geosciences, University of Arizona, Tucson, AZ 85721

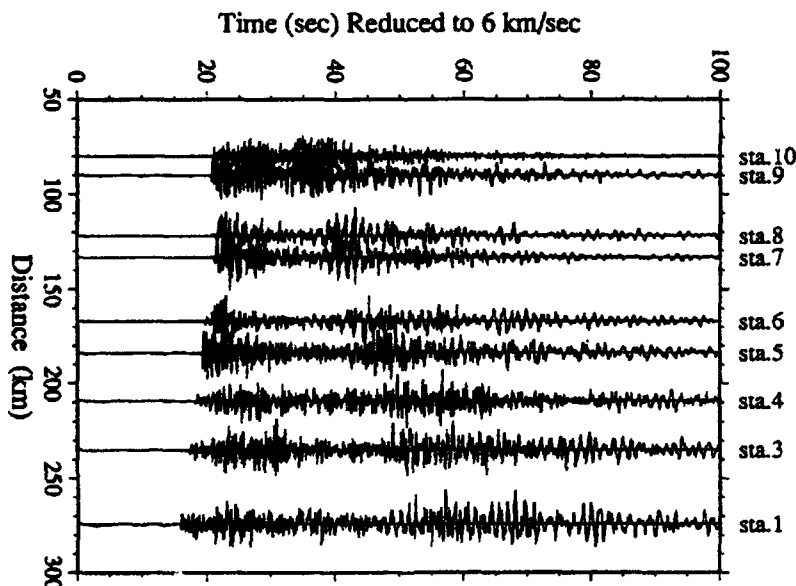
G. Zandt

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The University of Arizona recorded the Non-Proliferation Experiment (NPE) along an east-west profile between the Nevada Test Site and Lawrence Livermore National Laboratory's network station KNB (Kanab, Utah). The purpose of the profile is three-fold: (1) to investigate the development of regional phases  $P_n$ ,  $P_g$ ,  $S_n$ ,  $S_g$ ,  $L_g$ , and  $R_g$ , (2) to investigate the similarity of the NPE seismic signature to that of nuclear events detonated at N-Tunnel in the past, and (3) to investigate the effects of changing geologic environment on various seismic discriminants. We installed ten stations equipped with STS-2 seismometers (frequency band 40–0.05 Hz), Reftek digitizers, and GPS clocks. The closest station to the shot point is approximately 73 km. The profile had spacing of

approximately 20 km (the close spacing is essential to track phase development without aliasing).

The seismic profile begins in the Basin and Range and ends on the Colorado Plateau. This represents a remarkable change in geologic environments and is reflected in the seismic phase character. Both  $P_n$  and  $P_g$  are reduced in amplitude on the Plateau and show more complex scattering. Using  $L_g$  amplitudes to calculate magnitudes ( $m_{bLg}$ ), the profile gives an average yield of the explosion of 1.5 kt. The yield estimate is a bit problematic because  $L_g$  is not well developed at travel distances of less than 200 km. The Plateau apparently causes scattering of energy onto the transverse component, and the surface waves show Rayleigh wave-like polarization.



■ Figure 1. University of Arizona seismic profile of NPE: a reduced travel-time profile of the vertical component of the seismic wavefield. Note the change in character of the wavefield between stations 4 and 5.

# Regional Seismic Observations of the NPE at the Livermore NTS Network

William R. Walter, Howard J. Patton, and Kevin Mayeda

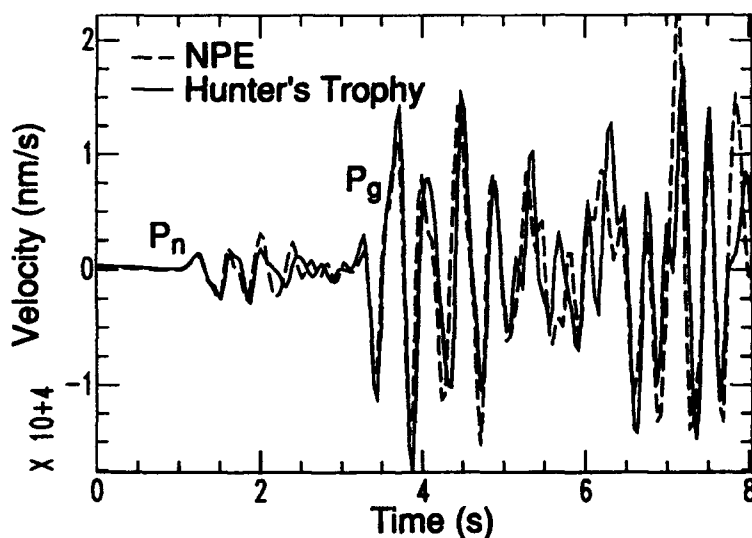
Lawrence Livermore National Laboratory, Earth Sciences Division, L-205, Livermore, CA 94551

The Non-Proliferation Experiment (NPE), a 1-kiloton chemical explosion in N-Tunnel at Rainier Mesa on the Nevada Test Site (NTS), was recorded by the four-station, regional seismic Livermore NTS Network (LNN). In this study we compare the NPE's seismic yield, frequency content, and discrimination performance with other NTS events recorded at LNN. Preliminary findings include:

- The NPE LNN average magnitudes are 4.16 for  $m_b(P_n)$  and 4.59 for  $m_b(L_g)$ . Using published magnitude-yield relations gives nuclear equivalent yields of 2.3 and 2.2 kilotons respectively, implying enhanced coupling of chemical relative to nuclear explosions.
- A comparison of seismograms from the NPE with similar magnitude N-Tunnel nuclear explosions

shows remarkable similarity over the frequency band 0.5 to 5.0 Hz (Figure 1). Outside this band the explosions show more variability, with the NPE having the least relative energy below 0.5 Hz and the most energy above 5 Hz when scaled by magnitude. Considering the variability within the N-tunnel nuclear explosions, these low- and high-frequency NPE-nuclear differences may not reflect chemical-nuclear source differences.

- Two short-period discriminants,  $P_n/L_g$  and  $P_g/L_g$ , were studied using a large set of NTS nuclear explosions and earthquakes. The NPE  $P/L_g$  ratios are very similar to those of other N-Tunnel nuclear explosions and NTS explosions in general.



■ Figure 1. A comparison of the initial velocity records from the NPE chemical explosion and the Hunters Trophy nuclear explosion recorded at the Livermore station MNV about 219 km away. These vertical component traces have been shifted so the first arrival time is the same and the start of the regional P phases labeled. The instrument response is flat in displacement from about 0.1 to 5 Hz.

# **Modeling of the NPE and a Nuclear Explosion with Finite Sources and Empirical Green's Functions**

*Lawrence Hutchings, Peter Goldstein, Stephen Jarpe, and Paul Kasameyer  
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To better understand the source characteristics of nuclear and chemical explosions for purposes of discrimination, we modeled the NPE chemical explosion and the Bristol nuclear explosion. We modeled both an elastic source on a spherical surface and an inelastic, expanding spherical volume source. Seismograms were synthesized at several sites to test the validity of our source models. We used

smaller chemical explosions detonated in the vicinity of the working point to obtain empirical Green's functions. In computations, Green's functions are identical for chemical and nuclear explosions. Empirical Green's functions contain all the information of the geology along the propagation path and at recording site. Therefore, we were able to reduce the variability in modeling the source of the larger events.

## ***Nonseismic Monitoring Methods***

### **Ionospheric Measurements of the NPE**

*T. Joseph Fitzgerald*

*Los Alamos National Laboratory, Los Alamos, NM*

The detection of explosions using ionospheric techniques relies on measuring perturbations induced in radio propagation by acoustic waves which disturb the electron density of the ionosphere. We have proposed such techniques as a supplement to seismic for discrimination of underground nuclear explosions from commercial mining expositions. The nighttime ionosphere presents a difficulty for the detection of explosions because the electron density in the altitude range from 90 to 200 km decays after sunset without a supply of solar ionizing radiation. On the other hand, acoustic waves produced by weak explosions reach a maximum amplitude in the altitude range of 100 to 150 km and are highly attenuated at altitudes above 200 km. For safety reasons, most planned explosions are conducted during daylight,

which has limited our experimental measurements during nighttime. However, a recent opportunity for a nighttime measurement occurred in connection with the Non-Proliferation Experiment, which consisted of the detonation of a large chemical charge underground at the Nevada Test Site near midnight local time. Our results, based on a new concept of monitoring medium-frequency commercial radio broadcasts, were negative. Simulations based on our daytime measurements of the Hunters Trophy event indicate that if the acoustic disturbance were the same an ionospheric signature should have been detectable. The most likely explanation of the negative result is that we did not achieve our goal of sensing the lower ionosphere because of constraints of path geometry and transmitter frequencies.



## **Infrasonic Measurements of the NPE**

*Rodney W. Whitaker, Susan Noel, and Wayne Meadows  
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An array of low-frequency, infrasonic microphones at St. George, Utah, detected the atmospheric signal from the Non-Proliferation Experiment (NPE) on 9/22/93, executed in Area 12 of the Nevada Test Site. Because the depth of burial for this event was great, close to 400 meters, the surface ground motion would be small, which means that the atmospheric signal

would be small. Given the time of year and source array distance, 231 km, a signal would be expected in 12.5 to 13.5 minutes. The observed signal arrived slightly later than this with a peak correlation coefficient of 0.9. The slightly delayed arrival means that the upper atmospheric winds were somewhat weaker than average for this time of year.

## Hydroacoustic Observations of the NPE

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*Lawrence Livermore National Laboratory, Livermore, CA*

*G. D'Spain*

*Marine Physical Laboratory, Scripps Institution of Oceanography, La Jolla, CA*

The NPE was observed by three hydroacoustic arrays located off of the coast of California: (1) a vertical line array deployed by the Marine Physical Laboratory, Scripps Institution of Oceanography, (2) a special sonobuoy array deployed for the Lawrence Livermore National Laboratory by COM-PATWINGSPAC, U.S. Navy, (3) an array of the U.S. Navy SOSUS system. The P phase from the event was very clear on the vertical line array, just visible on the sonobuoy array, and moderately well recorded on the SOSUS system.

Hydroacoustic monitoring of continental events is in its infancy when compared to seismic monitoring. The principal issue is whether hydrophone arrays can

be used to supplement land-based seismic networks to monitor continental regions bounded by oceans. The NPE observations and observations of Hunters Trophy show detectable signals for magnitude 4.4 events at 600 kilometers. Observations of aftershocks of the Landers earthquake show detectable signals for magnitude 3 events at 320–360 kilometers. Initial results indicate that vertical line arrays are best for monitoring seismic body phases. The orientation of vertical arrays permits separation of the predominantly horizontally traveling waveguide noise of the oceans from vertically traveling pressure waves converted from seismic body phases at the sea floor.

## ***On-Site Inspection Activities***

### **EMP from a Chemical Explosion Originating in a Tunnel**

*Bob Kelly*

*P-14, MS D410, Los Alamos National Laboratory, Los Alamos, NM 87545*

Electromagnetic pulses generated by a chemical explosion deep in a tunnel have been detected by sensors placed on both sides of the portal. These detectors consisted of antennas, current transformers, B-dots, and D-dots. The main objective was to collect data for nonproliferation studies complementary to and in cooperation with seismic methods. The electric field strength at the portal was computed from the data to be on the order of 50 millivolts per meter,

with a Fourier transform indicating that most of the energy occurs below about 3 MHz. Several of the sensors displayed periodic sharp spikes probably not related to the device. Surface-guided waves were detected along power and ground cables plus the railroad track. Time-dependent surface current and charge were measured on the portal door, which serves as a secondary source for external radiation.

# The NPE and Gas Sampling as an On-Site Inspection Activity

Charles R. Carrigan

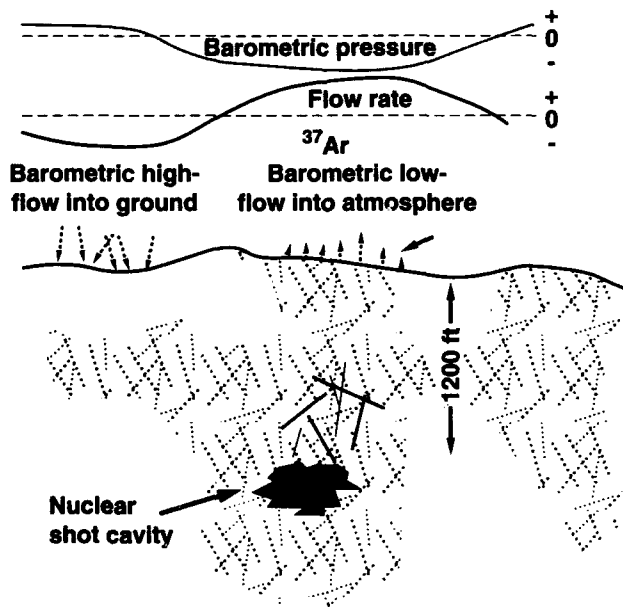
Earth Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA 94550

The Non-Proliferation Experiment (NPE) is contributing to the development of gas sampling methods and models that may be incorporated into future on-site inspection (OSI) activities. Surface gas sampling and analysis, motivated by nuclear test containment studies, have already demonstrated the tendency for the gaseous products of an underground nuclear test to flow hundreds of meters to the surface over periods ranging from days to months. Interaction between flows in fractures and in the porous matrix produces a "ratcheting" effect on the transport of gas in response to barometric pressure variations at the surface. Even in the presence of a uniform sinusoidal pressure variation, there will be a net flow of cavity gas toward the surface (Figure 1).

To test this barometric pumping effect on Rainier Mesa, gas bottles containing sulfur hexafluoride ( $\text{SF}_6$ )

and  $^3\text{He}$  were added to the predetonation cavity. Predetonation measurements of the background levels of both gases were also obtained on Rainier Mesa. The barometric lows associated with winter 1994 at NTS will provide the first real opportunity to detect the migration of tracers from the cavity.

Virtually all preceding, successful gas detection experiments have involved sites characterized by substantial fracturing around surface collapse features. For the NPE, the detonation point was approximately 400 m beneath the surface of Rainier Mesa, and the event did not produce significant fracturing or subsidence on the surface of the mesa. Thus, the NPE may ultimately represent an extreme but useful example for the application and tuning of cavity gas detection techniques.



■ Figure 1. Figure 1. Transport of gas from an underground nuclear test in response to barometric pressure variations at the surface.

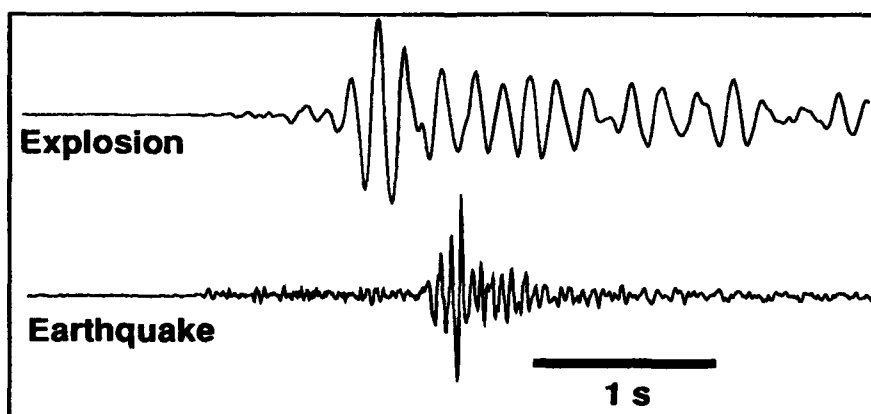
# Comparison of NPE Aftershocks with Other Nevada Test Site Events

Steven P. Jarpe, Peter Goldstein, and John J. Zucca

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We are interested in developing on-site inspection techniques for discriminating between explosions and earthquakes. It is well established that aftershocks from explosions can occur up to months after the event and tend to cluster around the emplacement point. If many aftershocks are recorded, the aftershock sequence is easily distinguishable from that of an earthquake since aftershocks from earthquakes tend to be located along planes. For small magnitude events, such as would likely be investigated under a Comprehensive Test Ban Treaty, the aftershock production rate after a few weeks is likely to be on the order of less than one a day. An inspection team is not likely to record enough events to distinguish their distribution. Therefore we are seeking to develop discriminants based on the waveforms of aftershocks.

We recorded aftershocks for several weeks after the Non-Proliferation Experiment (NPE) on a 16-component short-period seismic system deployed on Rainier Mesa around the ground zero of the NPE. In addition we have similar data from the Little Skull Mountain earthquake, which occurred in the southern part of the Nevada Test Site, and the Hunters Trophy nuclear test, which occurred near the NPE the previous year. We find that some of the aftershocks from Rainier Mesa are very low in frequency in contrast to aftershocks from the Little Skull Mountain earthquake (Figure 1). If these low-frequency aftershocks are found to be indicative of explosion seismicity, they could become an earthquake/explosion discrimination.



■ Figure 1. Aftershock recordings from the nuclear test Hunters Trophy and the Little Skull Mountain Earthquake.

## **Low-Altitude Overhead Imagery Acquisition Pre- and Post-NPE**

*William L. Pickles*

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*Janet E. Shines, David L. Hawley, Michael D. Pelan, and Stanley B. Brewster Jr.*

*EG&G RSL, Nellis AFB, Las Vegas, NV*

We have successfully acquired all the planned overhead imagery of the Non-Proliferation Experiment (NPE), for eight sets of overflights. The data set is very large and complete. We have acquired image mosaics of the area around the NPE Ground Zero (GZ). They were taken on six different days. The purpose for acquiring this data was to study changes that might be detected in the plants and soil on the top of Rainier Mesa as a result of the violent shaking of the ground caused by the explosion.

Each overflight acquired visible-light, color photographs using the RC30 large-format, forward-motion-compensated camera and 11 wavelength

bands of light from the blue to the thermal emission infrared, using the Deadlus AADS1268 multi-spectral, 11-channel, imaging scanner. Eight of the Deadlus bands have wavelengths in visible light, 0.42–1.05  $\mu$ . The remaining three bands are in the infrared, including a 8.5–12.5- $\mu$  infrared thermal-emission band and two infrared reflection bands, 2.08–2.35  $\mu$  and 1.55–1.75  $\mu$ . Sets of images were recorded at altitudes of 300 and 450 m above Rainier Mesa at pre-dawn on September 21, 22, 24, and 29, and at solar noon on September 10, 22, 24, and 30. Resulting spatial resolution on the ground is as good as 0.5 m for the hyper-spectral scanner data.

## **Low-Frequency Electromagnetic Measurements at the NPE and Hunters Trophy: A Comparison**

*Jerry J. Sweeney*

*Lawrence Livermore National Laboratory, Livermore, CA*

Sensors and recorders were deployed for both the Non-Proliferation Experiment (NPE) and Hunters Trophy to measure low-frequency (1–30 Hz) electric and magnetic fields accompanying the detonation. Two stations were used for each event, located at a slant range of about 500 m, with measurements of orthogonal horizontal electric field and orthogonal horizontal and vertical magnetic field. Signals were recorded digitally with a 200-Hz sampling rate. Separate magnetic and electric signals were recorded, which can be related both to the detonation and the arrival of the shock wave. The detonation

time signal from the nuclear explosion is a relatively short pulse occurring with no detectable delay (within 5 ms) after the detonation time. The signal from the chemical explosion is a broader waveform with delays ranging from 10–15 ms after the detonation time. The cause of the initial electromagnetic signal for both chemical and nuclear explosions is unknown; the differences between the NPE and Hunters Trophy results may be related to the different mechanisms involved with plasma generation between nuclear and chemical explosions.

## **Post-Test Geologic Observations Made at the Non-Proliferation Experiment Site, N-Tunnel, Nevada Test Site**

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Qualitative evaluations of damage resulting from an underground explosion can provide valuable information concerning the size of the charge, as well as the actual location of a clandestine detonation. However, caution must be exercised during the appraisal because the effects of an explosion are a function of many factors in addition to yield. Construction techniques, the physical properties of the surrounding rock, and the depth of burial are all important considerations when evaluating the effects of an underground detonation.

Raytheon Services Nevada documented underground and surface effects of the Non-Proliferation Experiment, as they have for all recent underground

weapons-effects tests conducted by the Defense Nuclear Agency. Underground, the extent of visible damage decreased rapidly from severe at the closest inspection point 100 m from the Working Point to insignificant 300 m from the Working Point. The severity of damage correlates in some instances with the orientation of the drift with respect to the shock-wave propagation direction. Also, most of the drifts near the explosion site had been shock conditioned by previous nearby nuclear explosions.

No evidence of the Non-Proliferation Experiment was visible on the mesa surface 389 m above the Working Point the day after the explosion.



## **Spontaneous Potential and Telluric Measurements on Rainier Mesa Related to the NPE**

*Jerry J. Sweeney, Lawrence Livermore National Laboratory, Livermore, CA*

We measured spontaneous potential (SP) on Rainier Mesa to see whether changes in subsurface electrical properties of rock related to the Non-Proliferation Experiment's explosion can be detected at the surface. A north-south line, repeated three times and running within 50 m of surface ground zero (SGZ) of Hunters Trophy and within 20 m of SGZ of the NPE, was measured before and after the NPE. An east-west line, with one end within 20 m of SGZ of the NPE, was also run before and after the NPE. There was a higher surface potential along the north-south line in the vicinity of the NPE after the detonation. This difference was not noted on the

east-west line. The north-south anomaly is much wider than predictions, based on simple SP models, would indicate to be possible for the depth of the source. A telluric line (0.025–0.1 Hz and 8.0 Hz) was also run along the same north-south line as the SP measurement, but farther to the west of SGZ for Hunters Trophy. There is a prominent high in the 8-Hz data in the northern part that may be related to a former nuclear test, but it could also be related to local geology. Results from these geophysical methods, while showing some promise for use in an on-site monitoring regime, also emphasize the need for repeatable background reference data.

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